Energetic Particles and Impacts Throughout the Heliosphere

- or -

How I Learned to ~~Stop~~ Start Worrying and ~~Love~~ Hate Ionizing Radiation

LWS/TIM 2014: C-SWEPA Project

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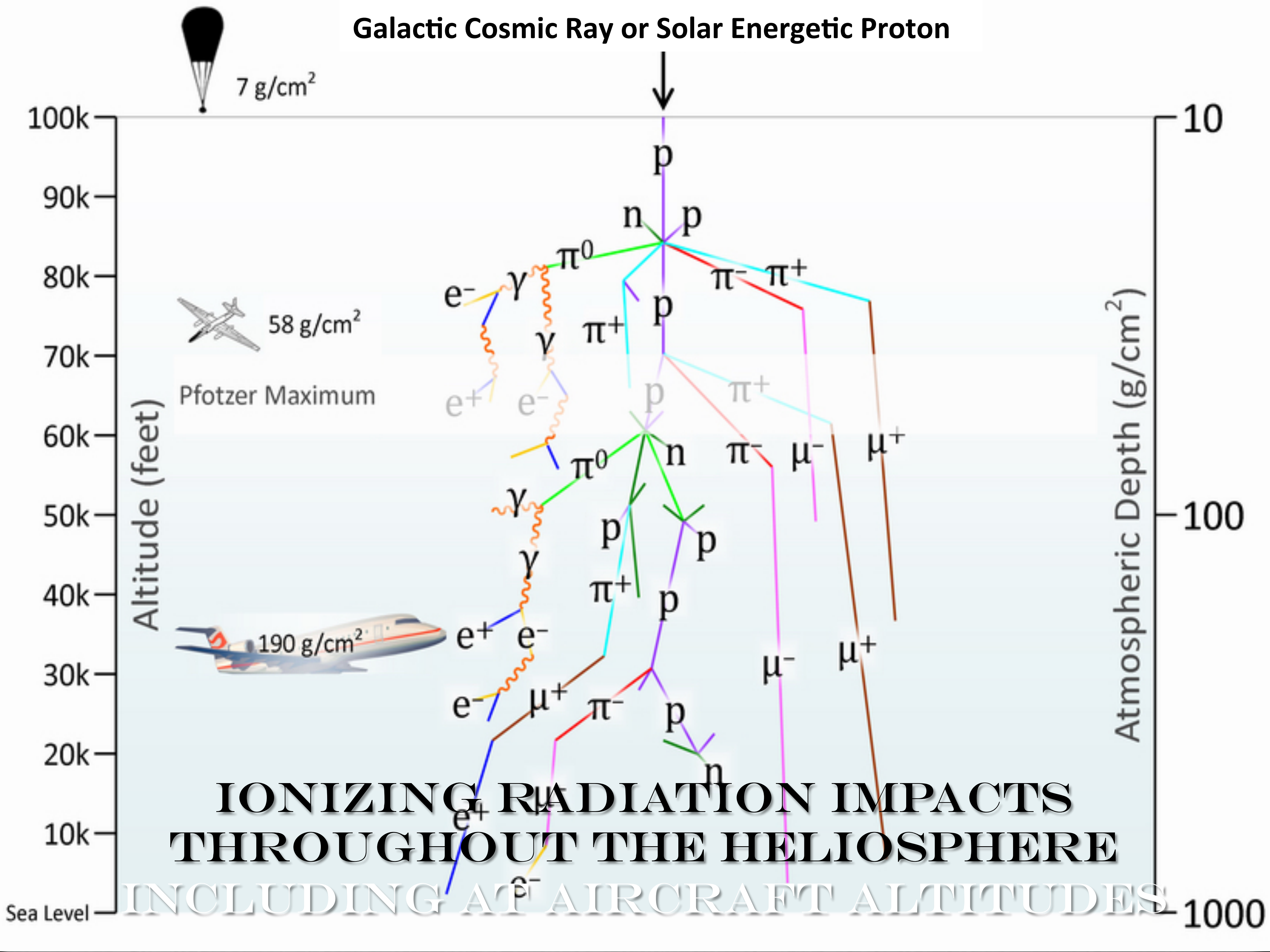
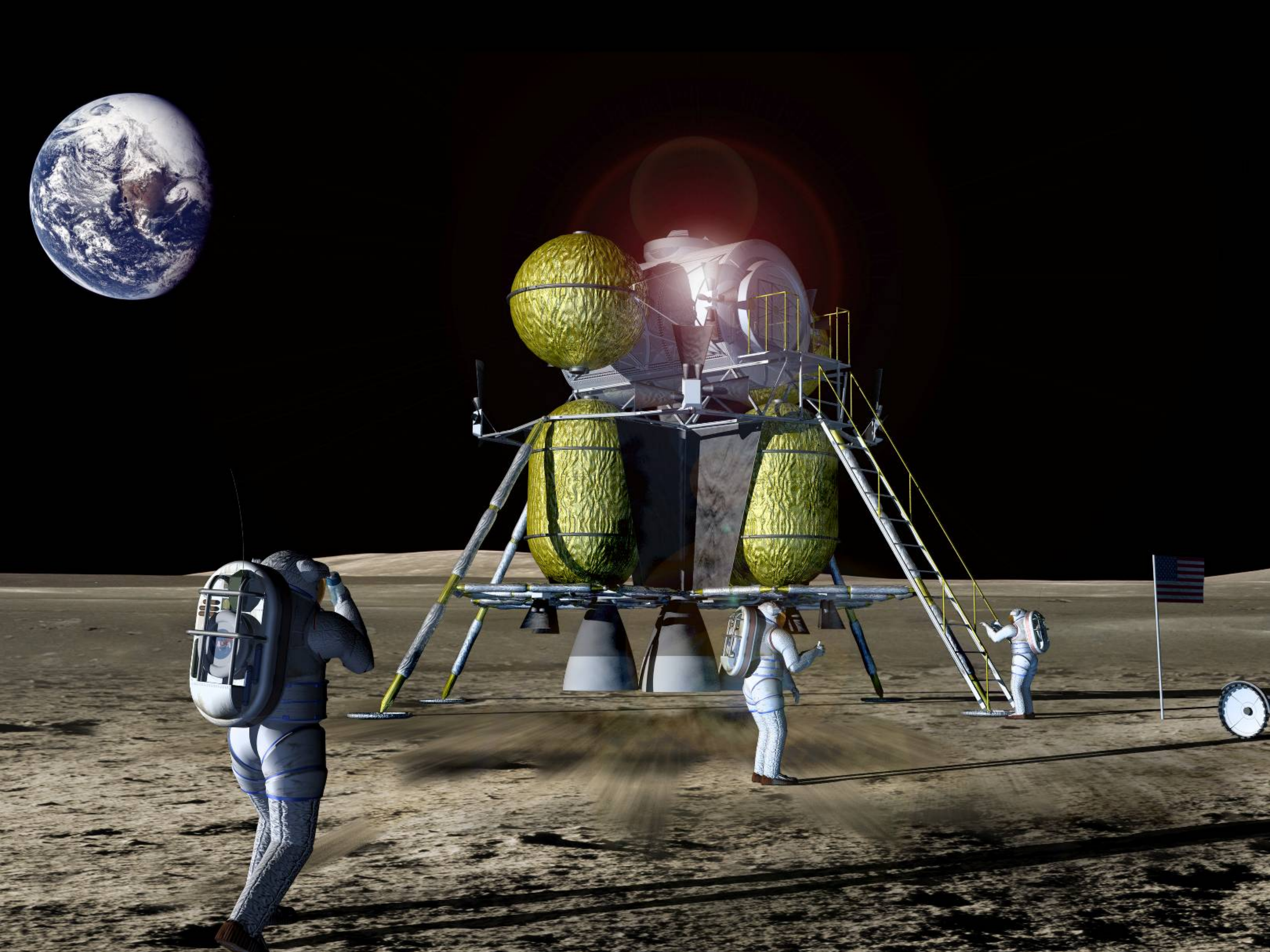
IONIZING RADIATION IMPACTS THROUGHOUT THE HELIOSPHERE INCLUDING AT AIRCRAFT ALTITUDES





What is “Ionizing Radiation”?

- Ionizing radiation is produced by particles and photons which ionize matter as they pass through and interact with it
  - When ionizing radiation occurs in human tissue and DNA, it damages it

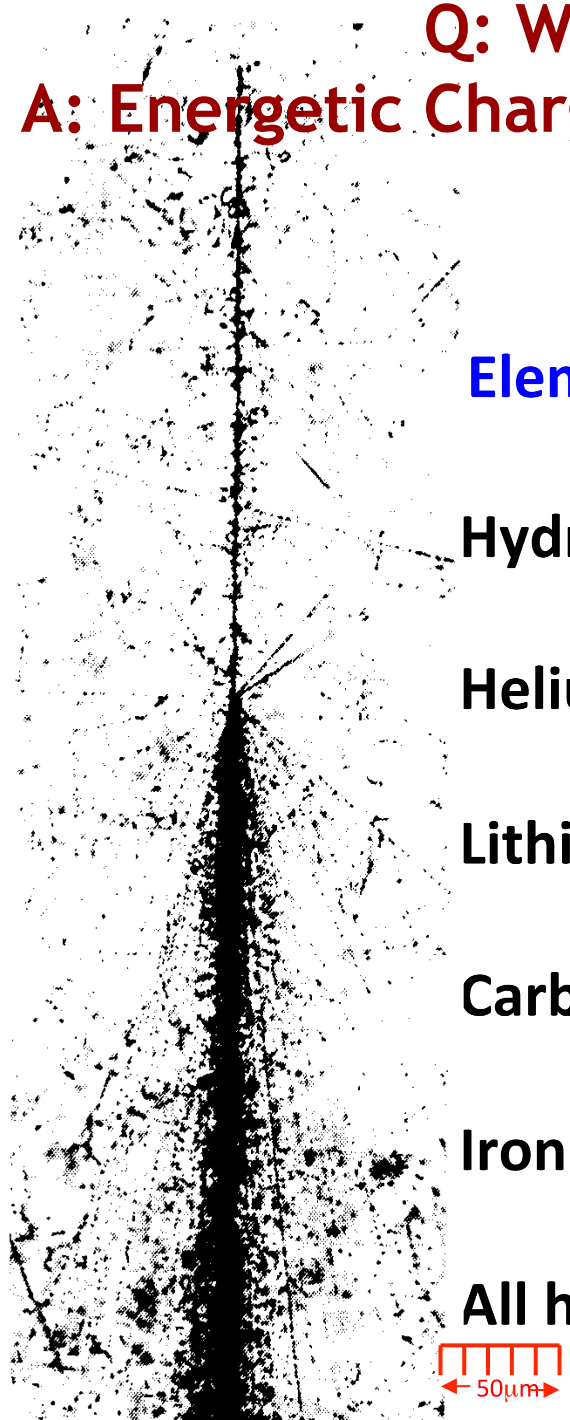
- On Earth, we use ionizing radiation (e.g., x-rays and charged particles) for medical imaging and cancer therapy
  - When used in a controlled fashion and in safe doses, ionizing radiation can be extremely beneficial to humans

- In deep space, high levels of ionizing radiation continuously from the cosmos but modulated by the Sun (galactic cosmic rays = GCR) and episodically from the Sun (solar energetic particles = SEP) bathe unprotected astronauts and robotic satellites in mostly uncontrolled ways, thereby posing health threats and risks

Cosmic Radiation: Fundamental Properties and Challenges

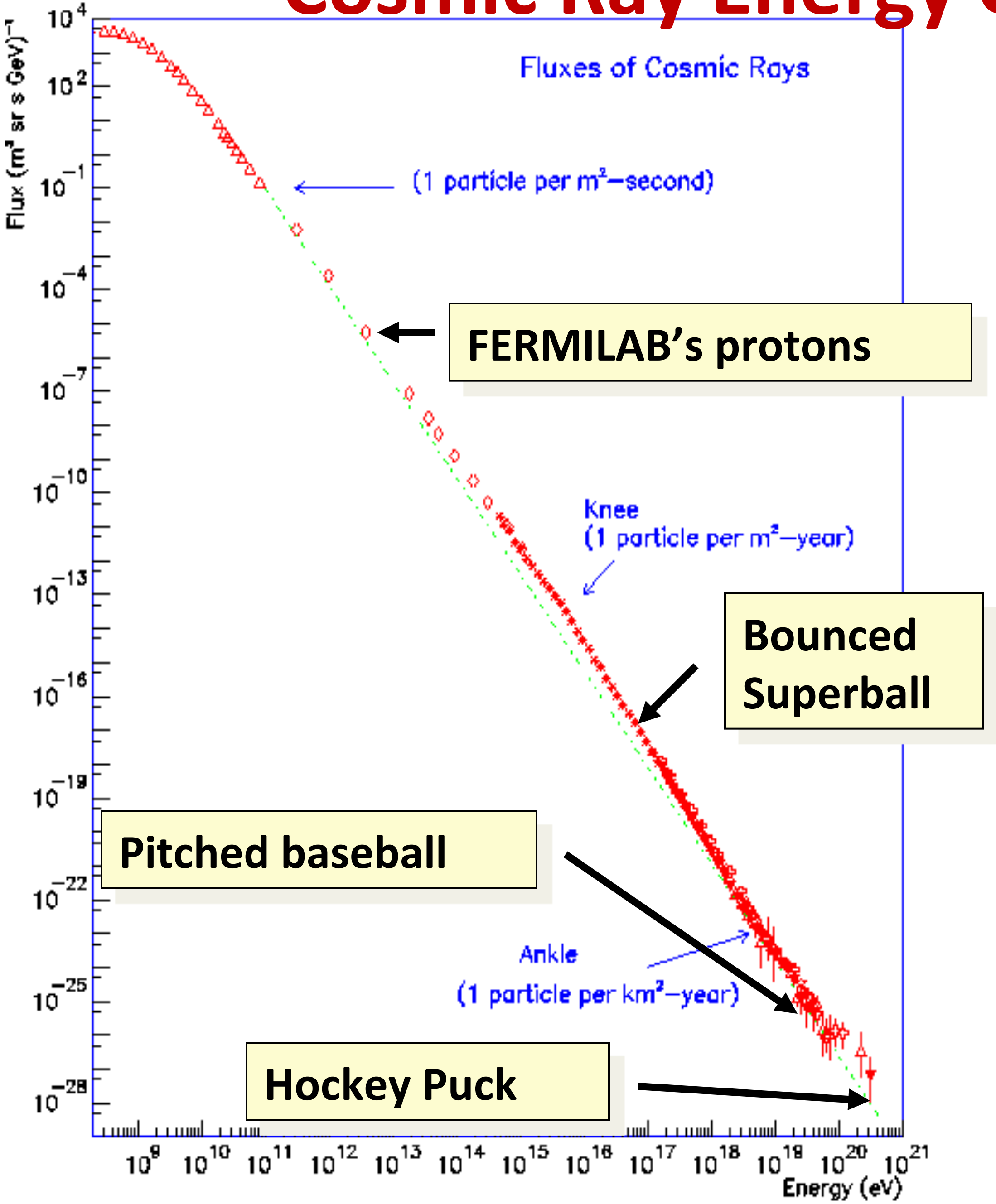
- High energy ionized particles
  - **Galactic** Cosmic Rays (GCRs – mostly protons)
  - Solar Energetic Particles (SEPs – mostly protons)
  - Secondary particles (lunar surface and spacecraft structure – neutrons and x-rays)
- Heavier ions (He, C, O, Fe) more destructive ion-per-ion
- Flux varies with the solar cycle
  - More complex magnetic field structures at solar maximum limit access of GCRs from galaxy into our inner solar system – unusual solar maximum gives pause for what the next decades may bring (**M. Lockwood recently upped likelihood to 25% of Grand Minimum occurring in next 40 years…)**
  - SEPs more common near solar maximum
- **Difficult to shield against**
  - **Penetrates thick materials easily**
  - **Fragments from shielding material actually <u>increase</u> radiation dose**

Q: What are Galactic Cosmic Rays?
A: Energetic Charged Particles Traveling Near Speed of Light



Element	Solar System Composition (relative #)	Primary Cosmic Ray Flux (#/m^{-2} sec)
Hydrogen (H)	1.00	640
Helium (He)	6.8×10^{-2}	94
Lithium, Beryllium, Boron	2.6×10^{-9}	1.5
Carbon, Nitrogen, Oxygen	1.2×10^{-3}	6
Iron (Fe)	3.4×10^{-5}	0.24
All heavier atoms	1.9×10^{-6}	0.13

Cosmic Ray Energy Comparisons



The highest energy Cosmic Rays are SUBATOMIC particles carrying the energy of MACROSCOPIC objects!

4 x 10^{21} eV = 60 joules

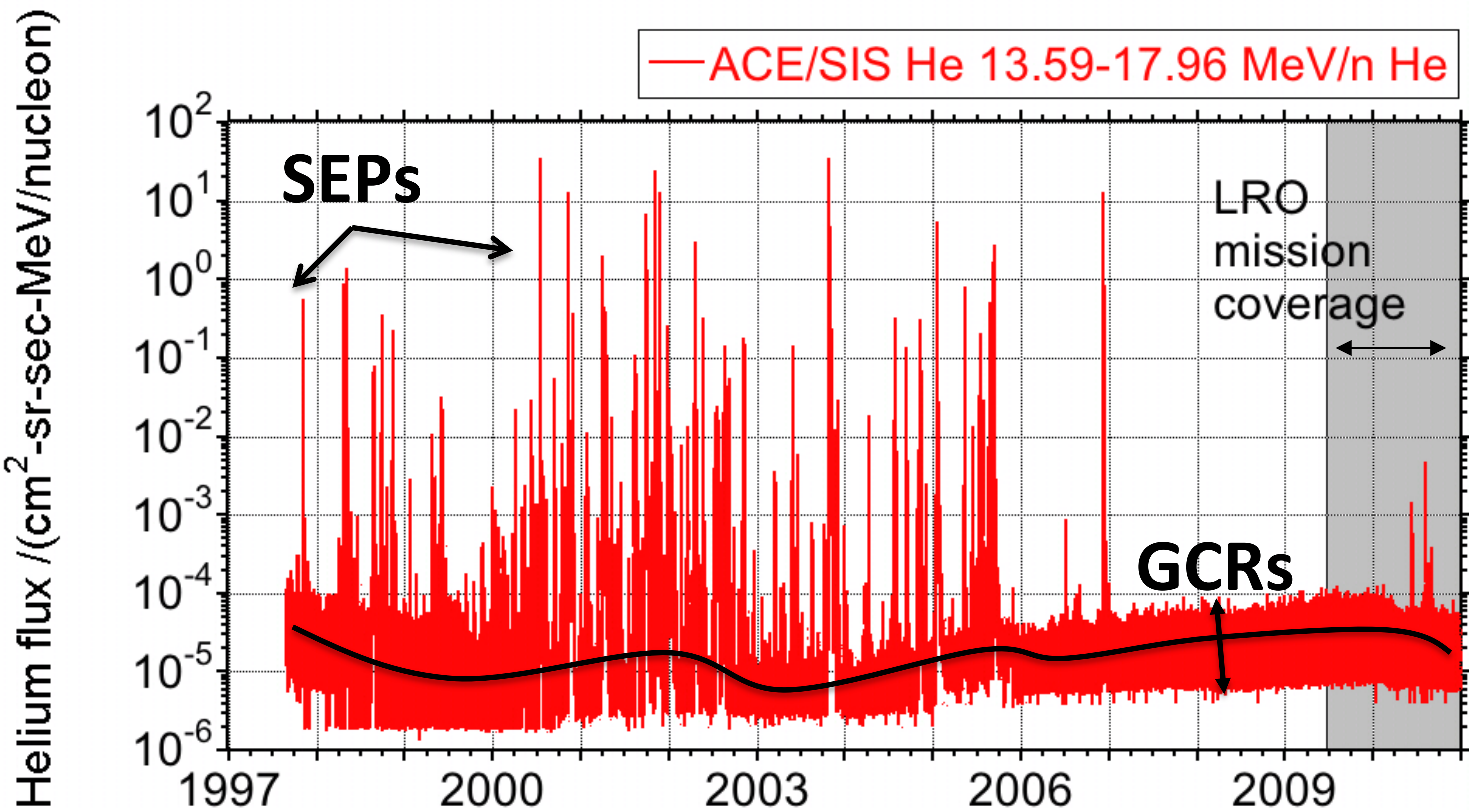
- **Accelerated largely in supernovae shock waves**

- **>10 MeV p+'s penetrate typical s/c shielding and pose energy deposit risks in man and machine**

Solar Particle Events

Solar protons are second source of ionizing radiation, appearing as episodic bursts on top of GCR intensity

The solar particle events seen in latest cycle have been much lower in intensity than the worst-case events from the last solar maximum, though have ramped up in frequency since 2012

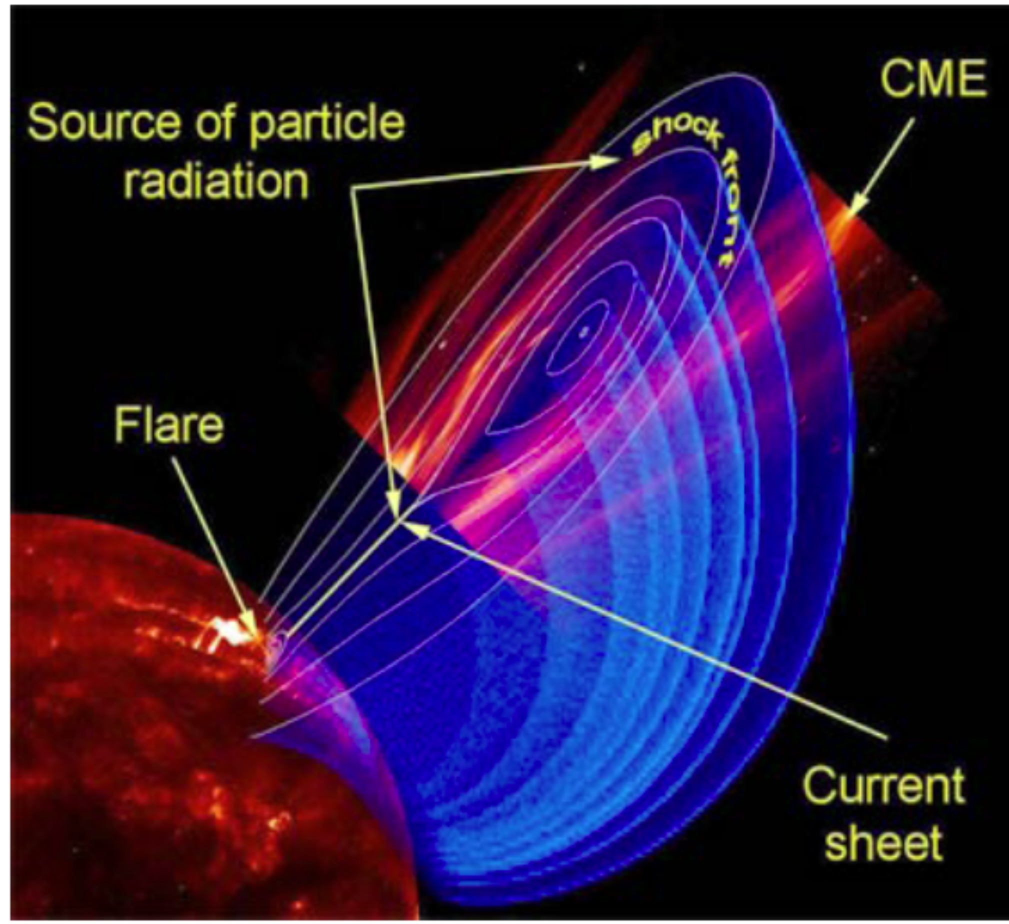


Solar Particle Events

- Solar Energetic Particles (SEPs) are energetic particles accelerated by processes associated with a solar source

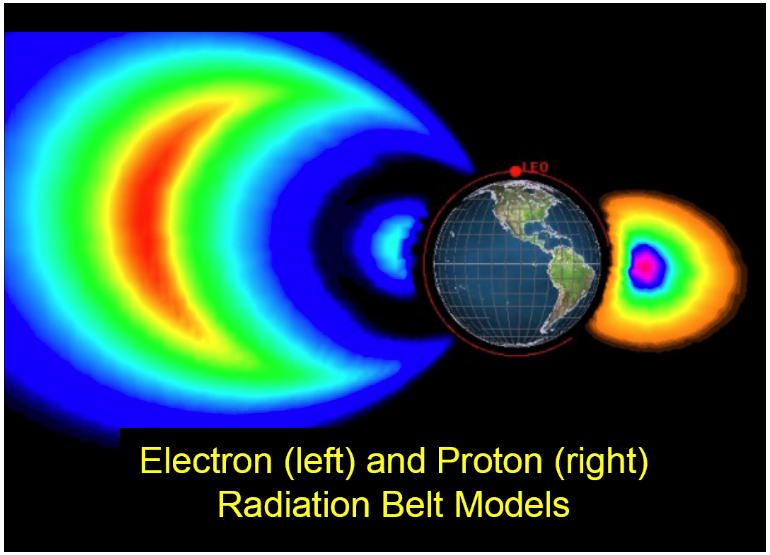
- SEPs originate from:
  - acceleration near a solar flare site; and
  - acceleration through interactions with interplanetary shock waves propagating away from the Sun

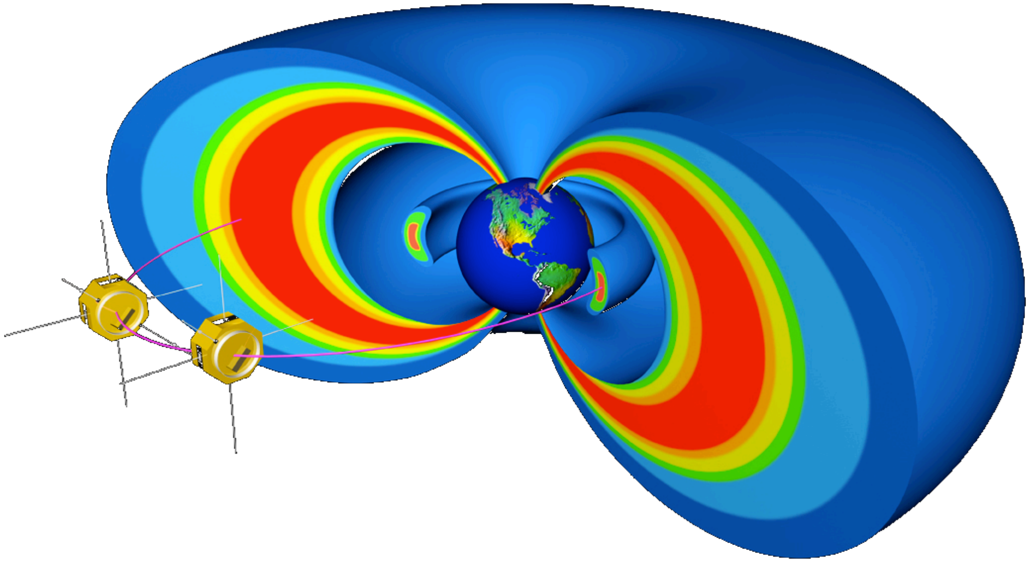
Sites of SEP Creation

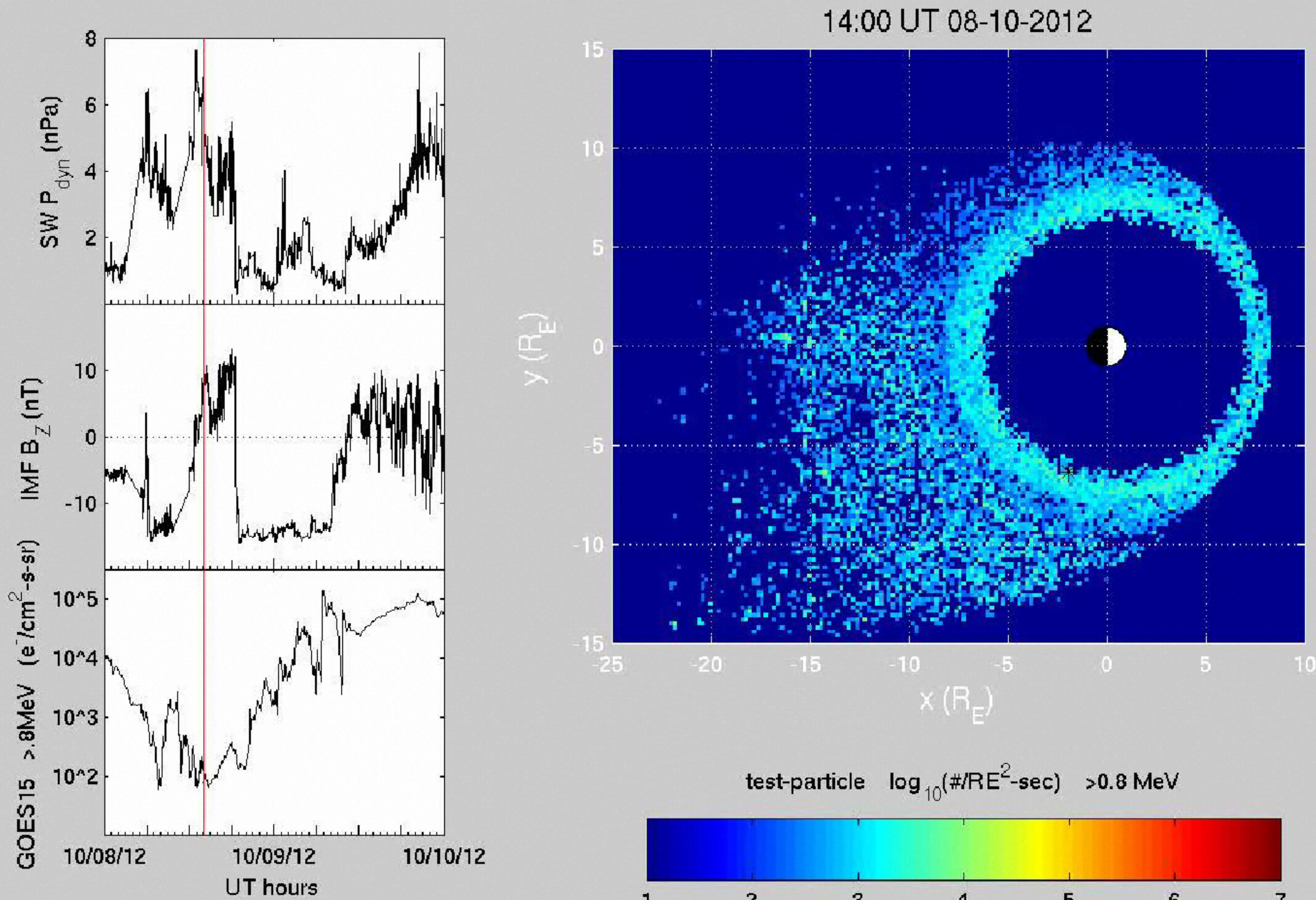


But wait – there's more!

- Van Allen Radiation Belts pose MORE radiation risks Discovered in 1958 by James van Allen with Explorer 1, the first US satellite
- **NASA/LWS** Van Allen Probes are discovering how the belts work and the effects of ionizing radiation; **seed population and acceleration microphysics *measured in situ* are absolutely CRITICAL for understanding**
- Recent HEPPA meeting underscored growing understanding that medium energy electron precipitation from Earth's radiation belts **important for stratospheric climate variability** (as important as solar UV changes)



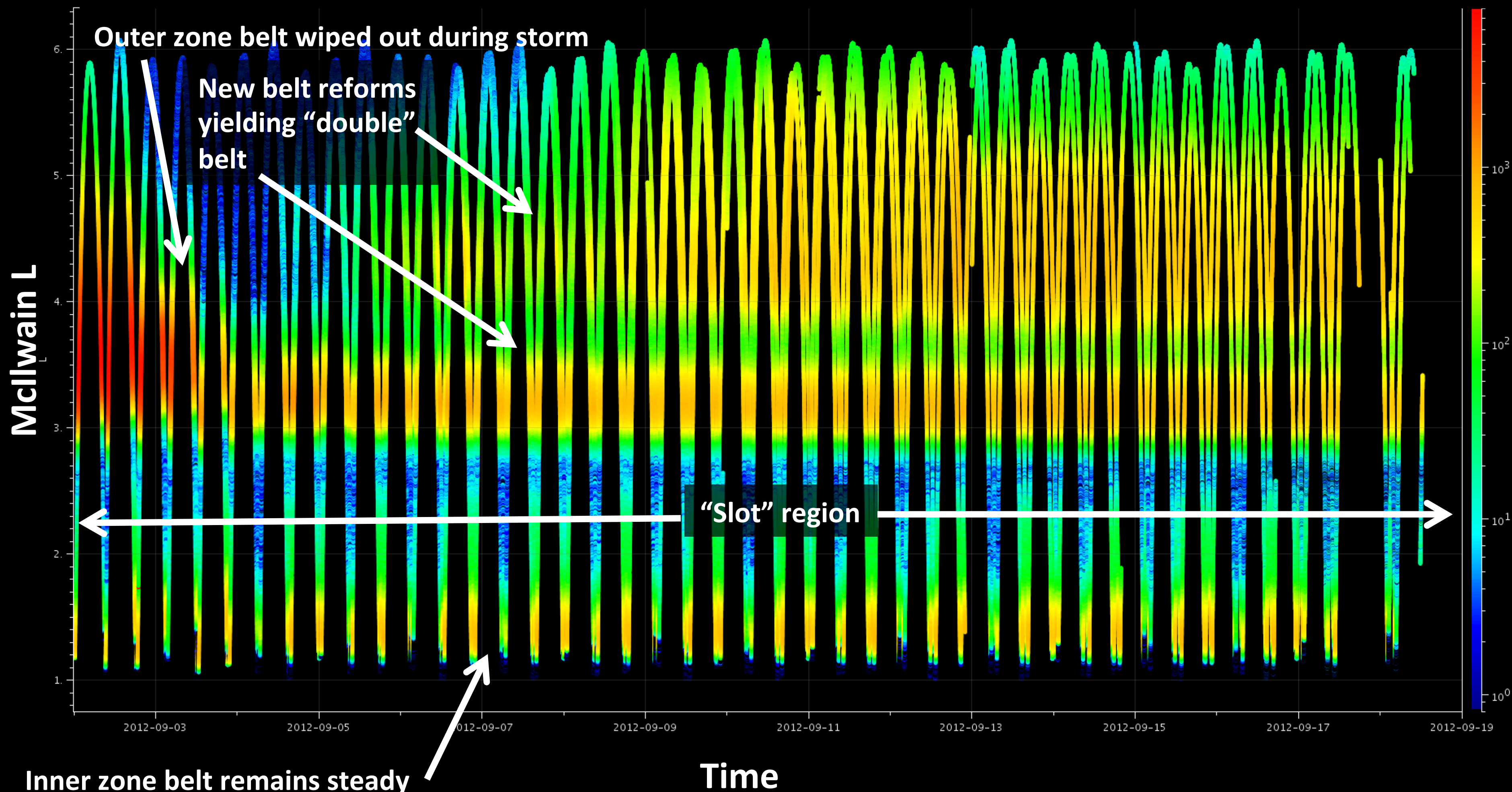




14:00 UT 08-10-2012
SW P dyn (nPa)
IMF B Z (nT)
GOES15 >.8MeV (e-/cm2-s-sr)
10/08/12
10/09/12
10/10/12
UT hours
y (RE)
x (RE)
test-particle log10(#/RE2-sec) >0.8 MeV

Van Allen Probe's RBSP–ECT REPT instrument witnesses ultra relativistic radiation belt destruction and reformation during storm which occurred immediately after instrument turn-on

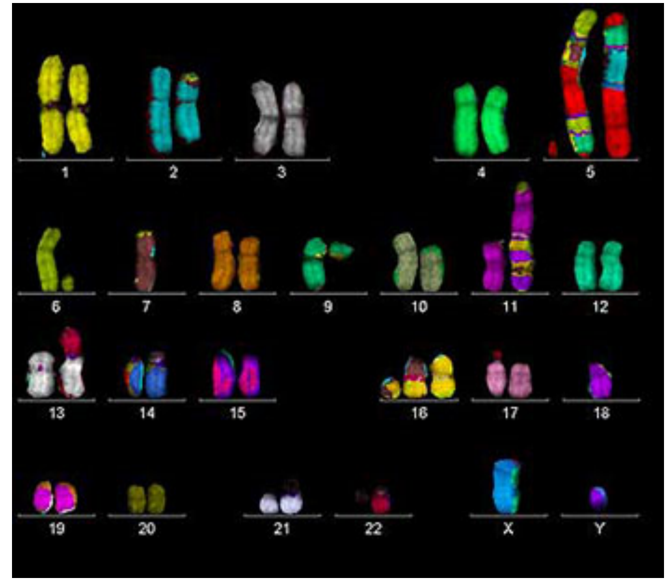
4.5 MeV e- flux observed by REPT-A and REPT-B (9/2 – 9/19)



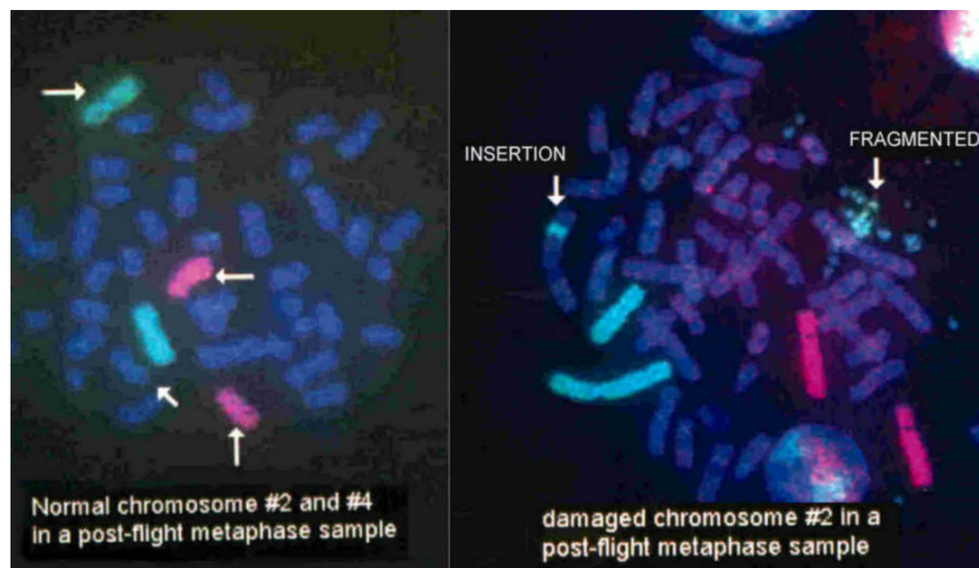
(From Baker et al., Science, 2013)

Dealing with Radiation: Human Spaceflight

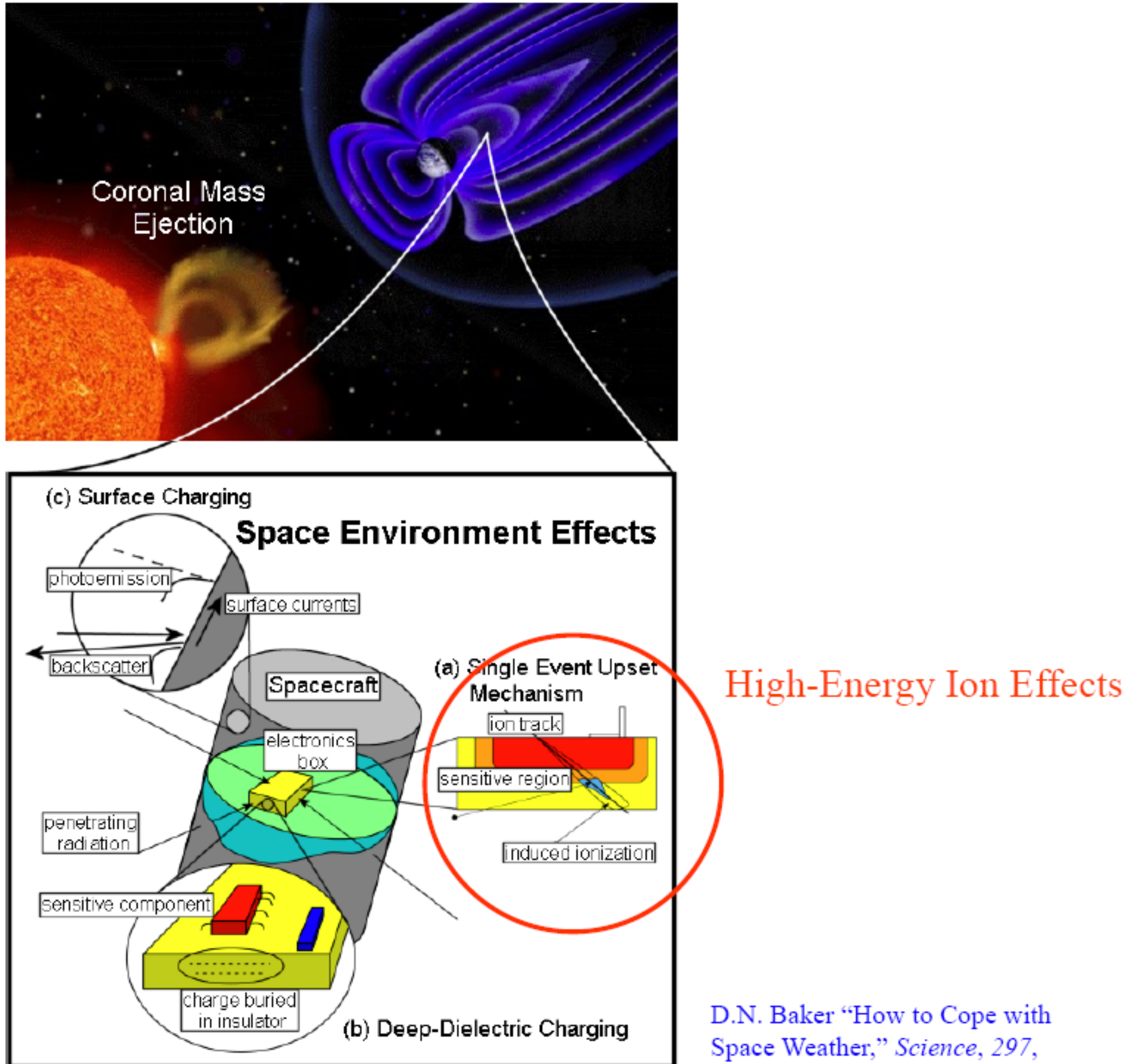
- ISS: 1 REM (Roentgen Equivalent Man, 1 REM ~ 1 CAT Scan)
  - Scintillations
  - Hardened shelter
- Spacesuit on moon 50 REM (Radiation sickness)
  - Vomiting
  - Fatigue
  - Low blood cell counts
- 300 REM+ suddenly
  - Fatal for 50% within 60 days



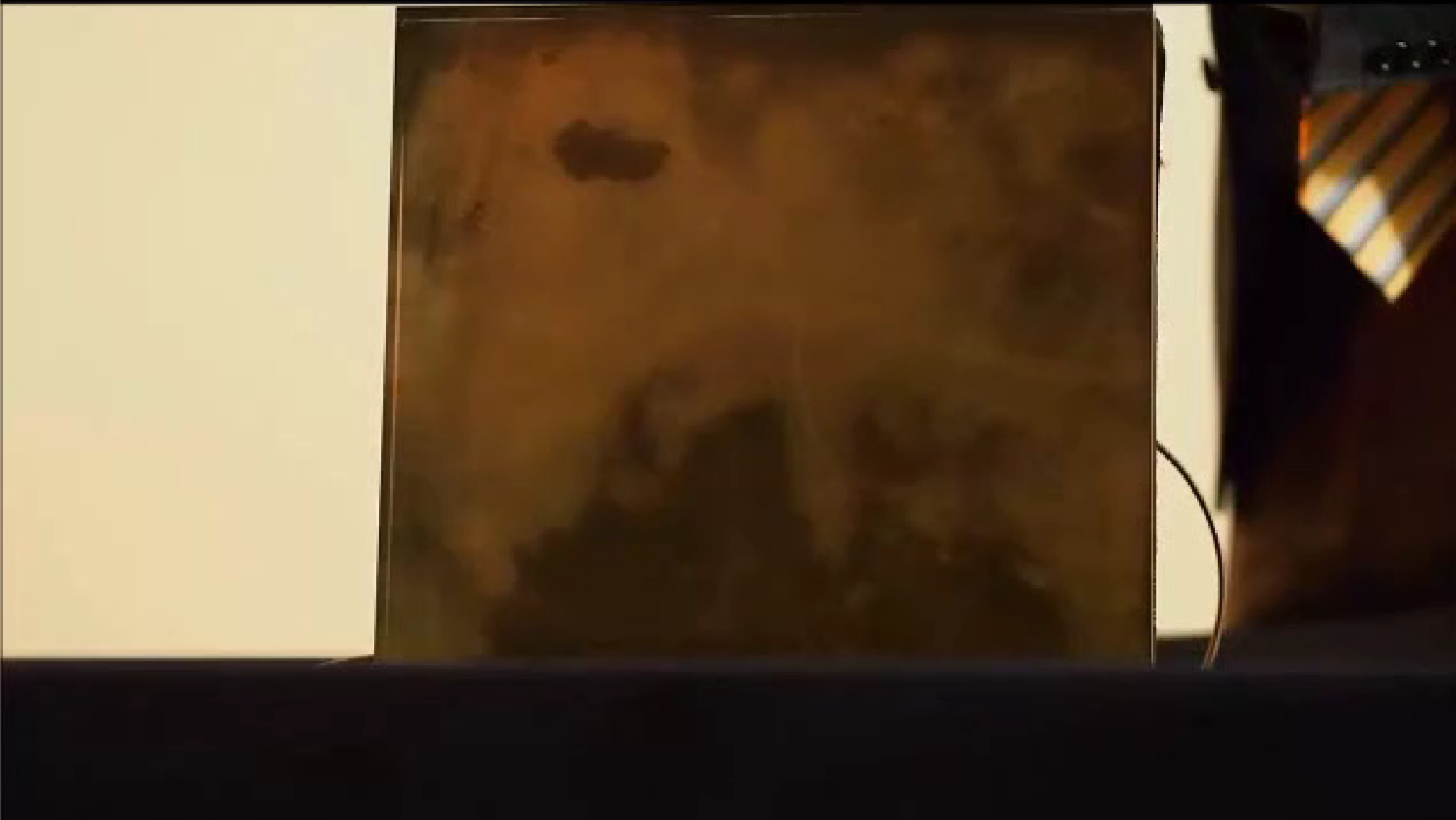
Human Chromosomes Showing DNA Damage From Radiation - Photo Credit: Massey University

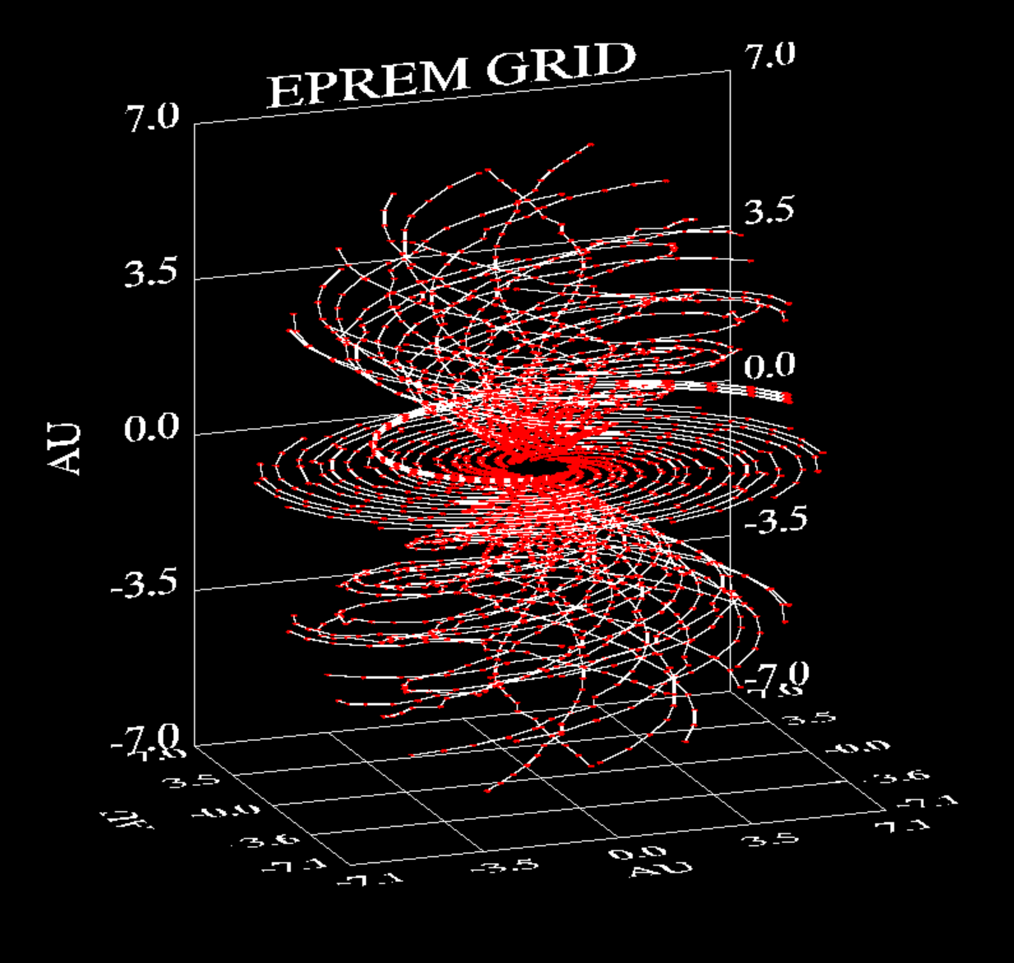


Dealing with Radiation: Satellite Effects



D.N. Baker "How to Cope with Space Weather," *Science*, *297*, 1486, 2002



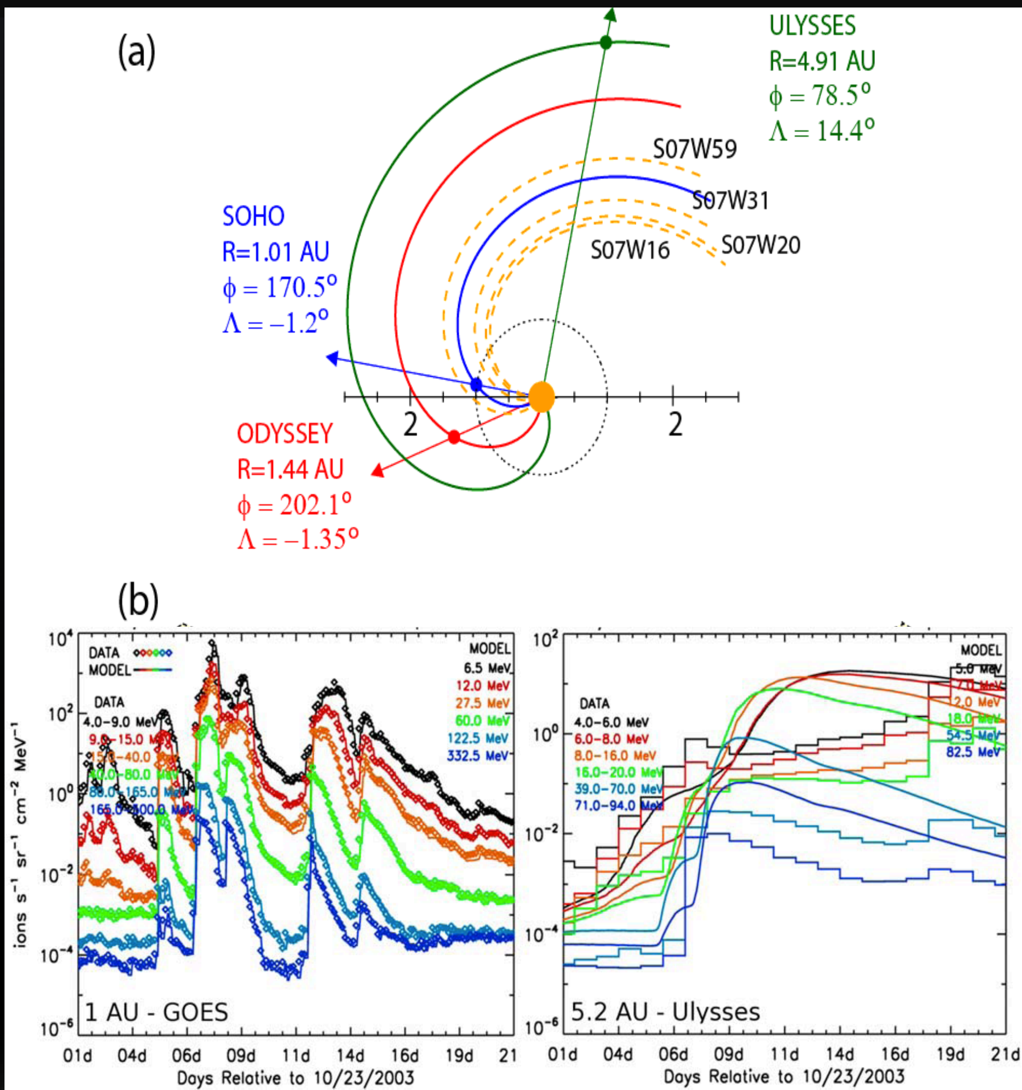


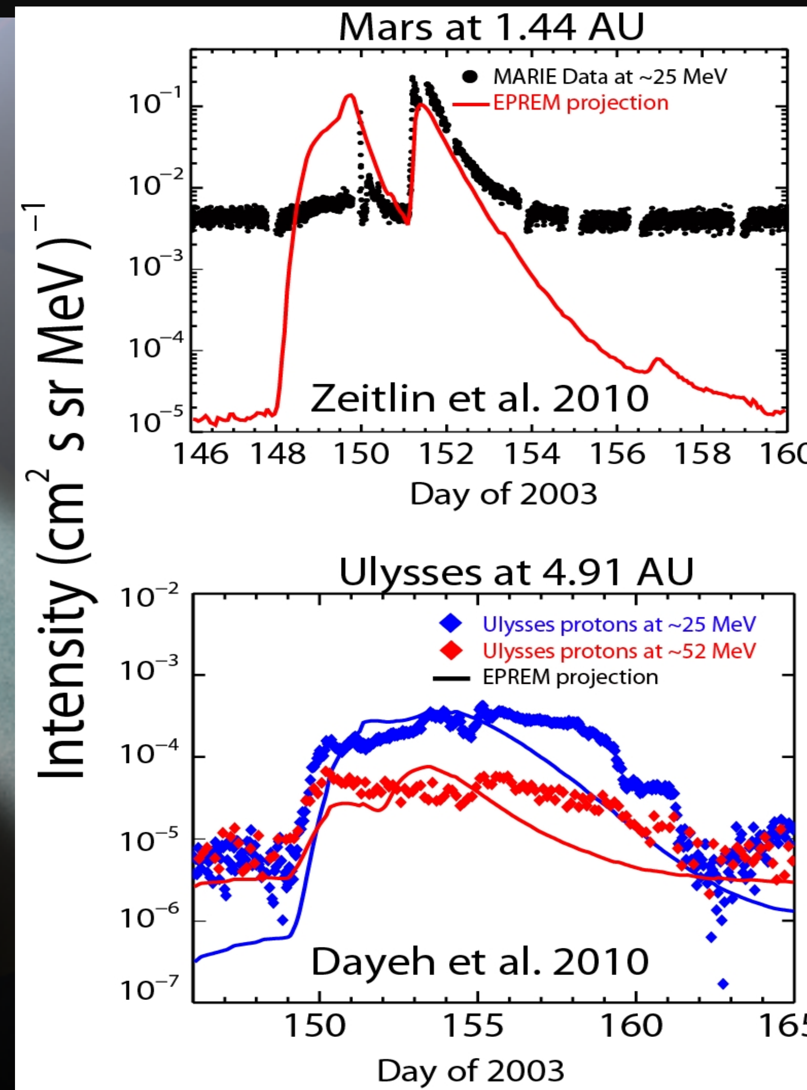
Focused Transport in Lagrangian Frame (Kota, 2005)

$$\left(1-\frac{(\vec{u}\cdot e_b)v\mu}{c^2}\right)\frac{df}{dt}+v\mu\frac{\partial f}{\partial z}+\frac{(1-\mu^2)}{2}\left[v\frac{\partial \ln B}{\partial z}-\frac{2}{v}e_b\cdot\frac{d\vec{u}}{dt}+\mu\frac{d\ln(n^2/B^3)}{dt}\right]\frac{\partial f}{\partial\mu}+\left[-\frac{\mu e_b}{v}\cdot\frac{d\vec{u}}{dt}+\mu^2\frac{d\ln(n/B)}{dt}+\frac{(1-\mu^2)}{2}\frac{d\ln B}{dt}\right]\frac{\partial f}{\partial \ln p}=\frac{\partial}{\partial\mu}\left(\frac{D_{\mu\mu}}{2}\frac{\partial f}{\partial\mu}\right)+S$$

- Cross-field Diffusion
- Drift

EMMREM has proved very successful at predicting SEP spectra and radiation dose estimates at different distances in the inner heliosphere. Figures below show two recent papers by which SEP time profiles, onset, and radiation estimates were successfully predicted at Mars (Odyssey) and Ulysses located at 1.44 AU and 4.91 AU, respectively. 1 AU measurement from ACE, SoHO, and GOES.



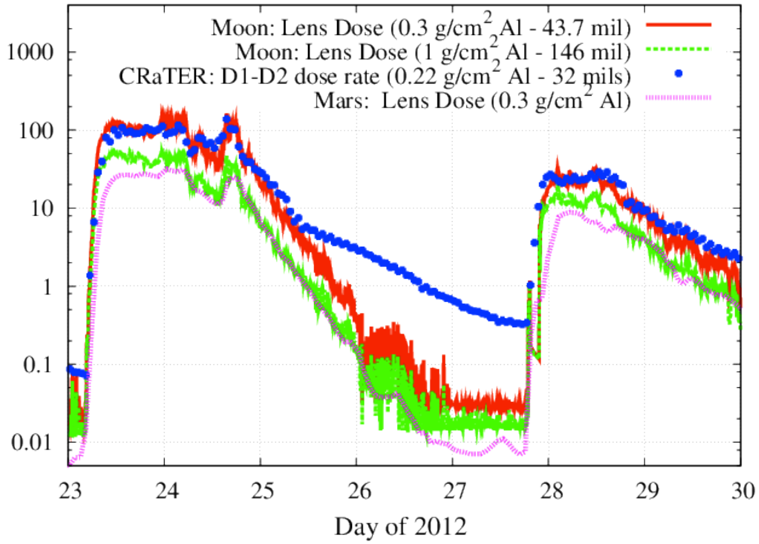


Validation with CRaTER

SEP Events During 2012: Indicators of Larger SEP Events in the New Cycle (24)

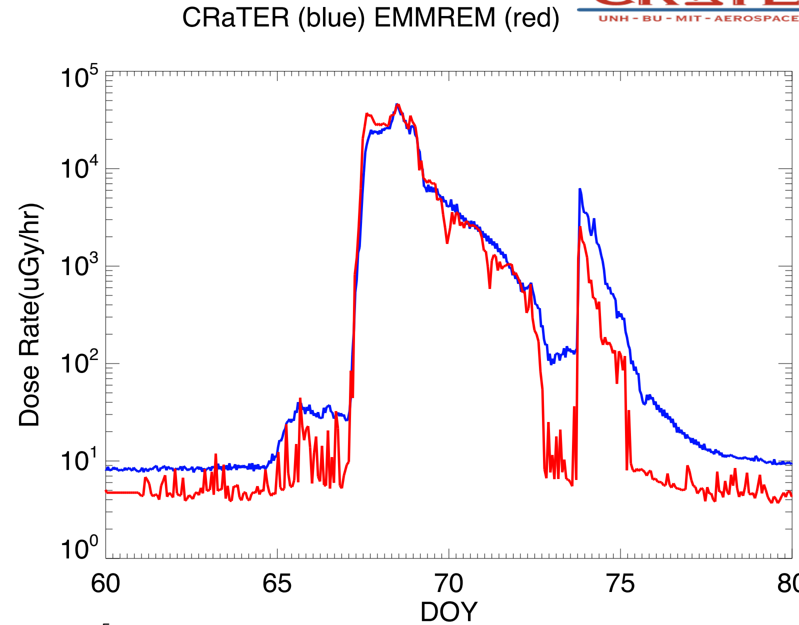
- **Shown here are the major SEP events of 2012 and the comparisons between CRaTER observations (blue) and prediccs predictions (red and green).**
- **Agreement reveals overall accuracy of models, while deviations likely reveal heavy ion contributions to dose observed by CRaTER**

Jan. 23rd, 2012 Event

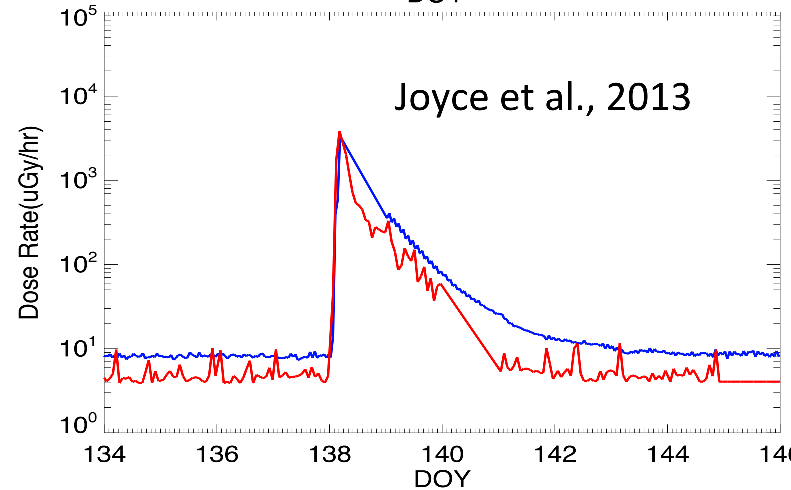


Schwadron et al., 2013

Mar 7, 2012 Event



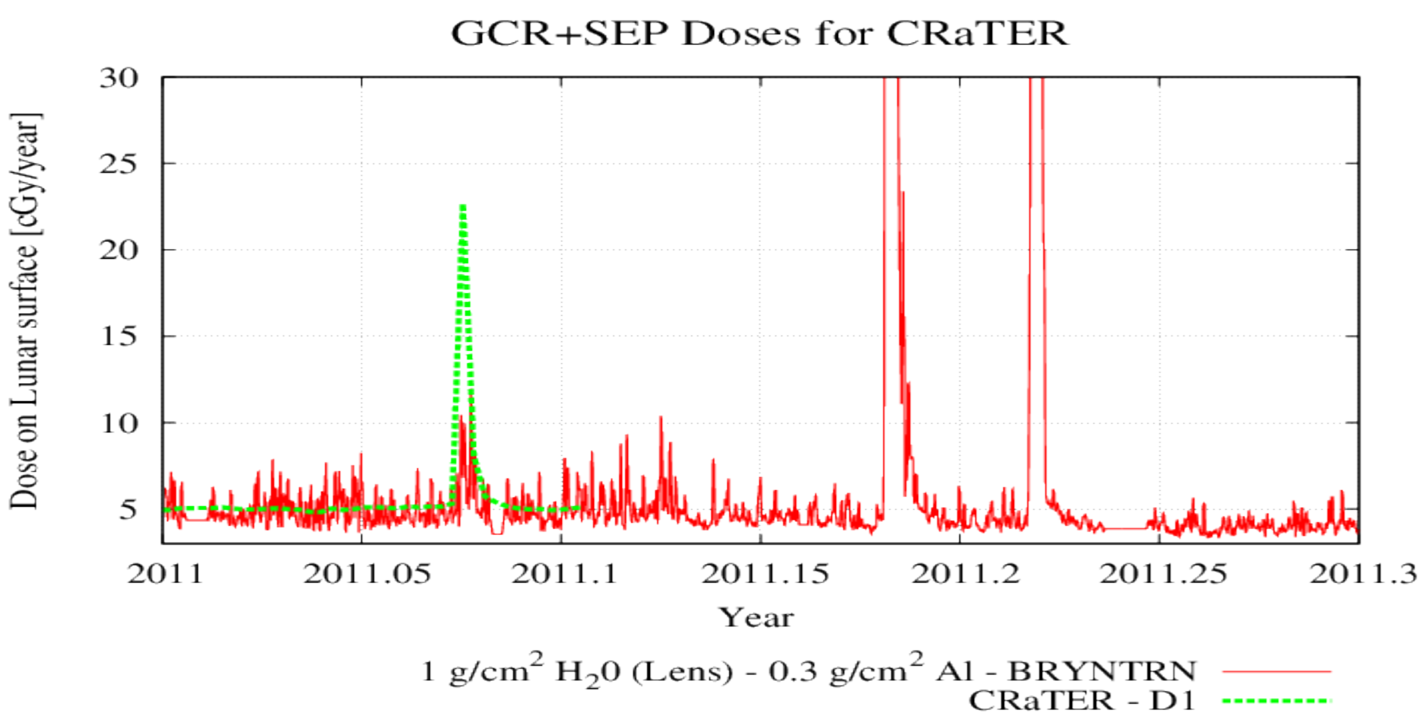
May 16, 2012 Event



Predicting Solar Particle Events – PREDICCs

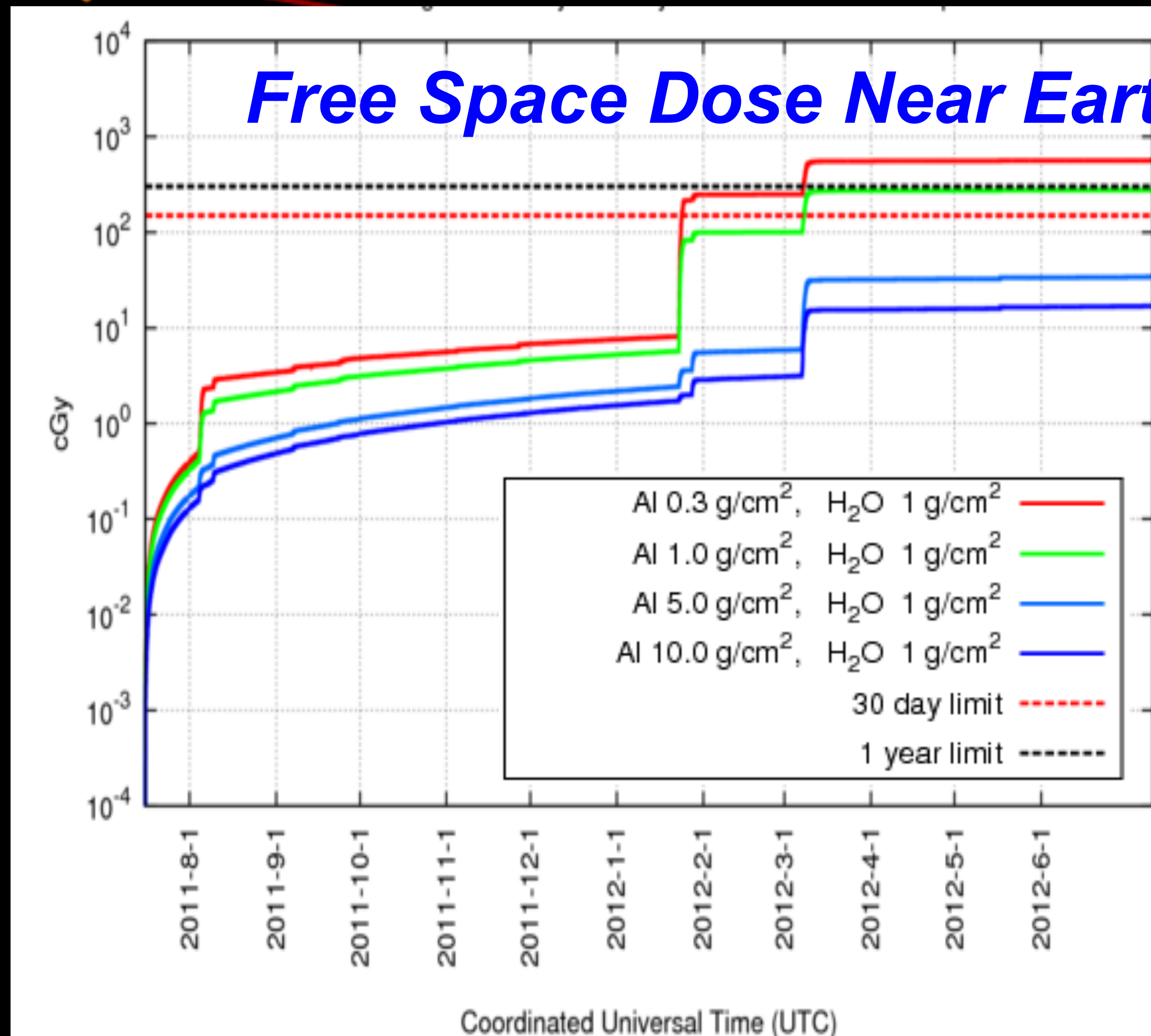
(P)redictions of radiation from (R)EleASE, (E)MMREM, and (D)ata (I)ncorporating (C)RaTER, (C)oStEP, and other (S)EP measurements (PREDICCs)

- EMMREM propagates energetic particles through the inner heliosphere to produce doses.
- Models compared with CRaTER data to improve forecasts of solar proton events, predictions of radiation environment beyond low Earth orbit

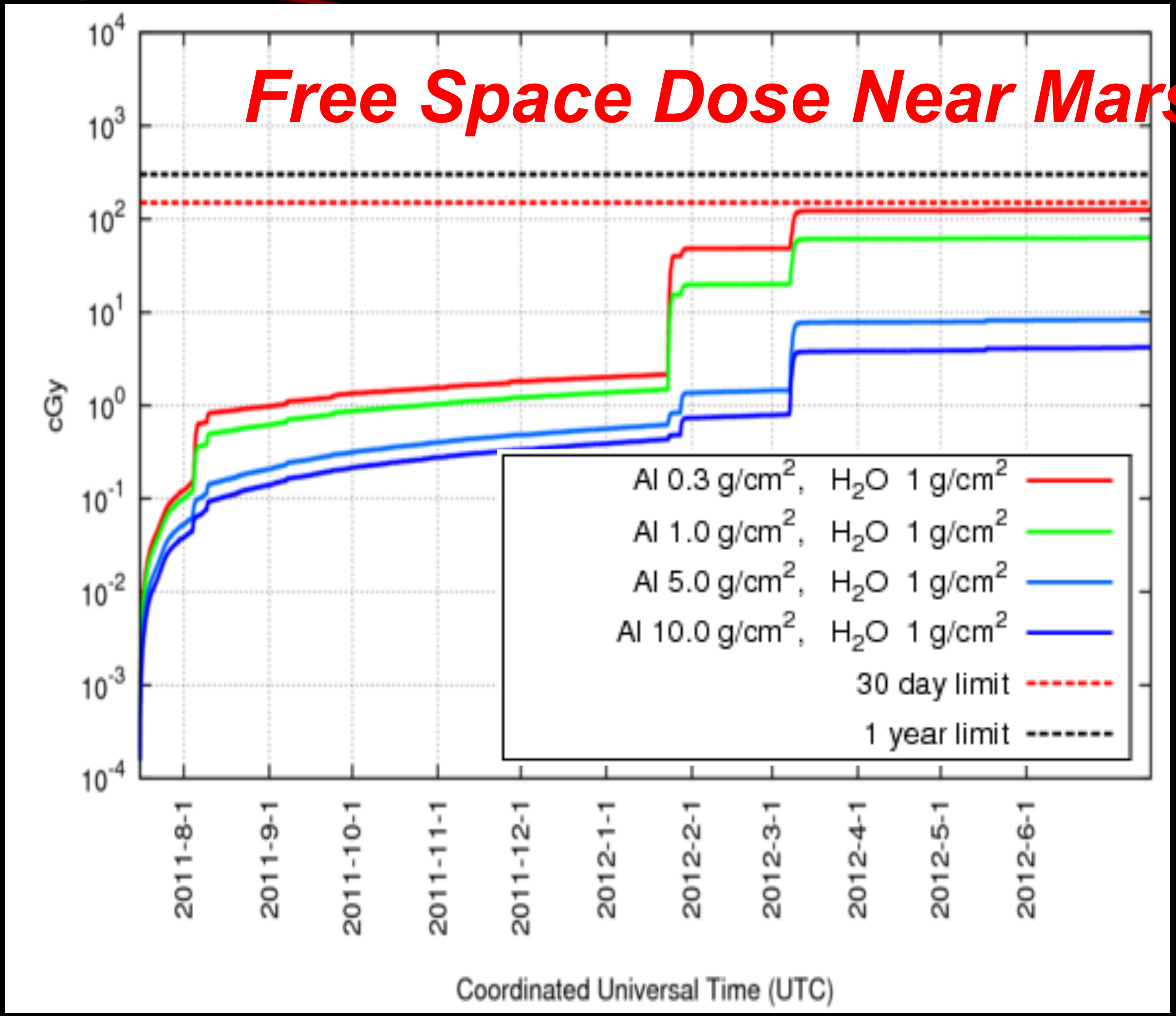


(Credit: Nathan Schwadron)

- System for Radiation Environment characterization (fluxes, doses, dose equivalents at Earth, Moon and Mars) on hourly thru yearly time frame
- Example: Snapshots of Current Yearly Doses at Earth and Mars
- Note: Exceeding 1-yr Free Space Dose Limits at Earth and Moon for < 1 g/cm^2 Al Shielding
- See more at [http://predicss.sr.unh.edu/](http://prediccs.sr.unh.edu/)



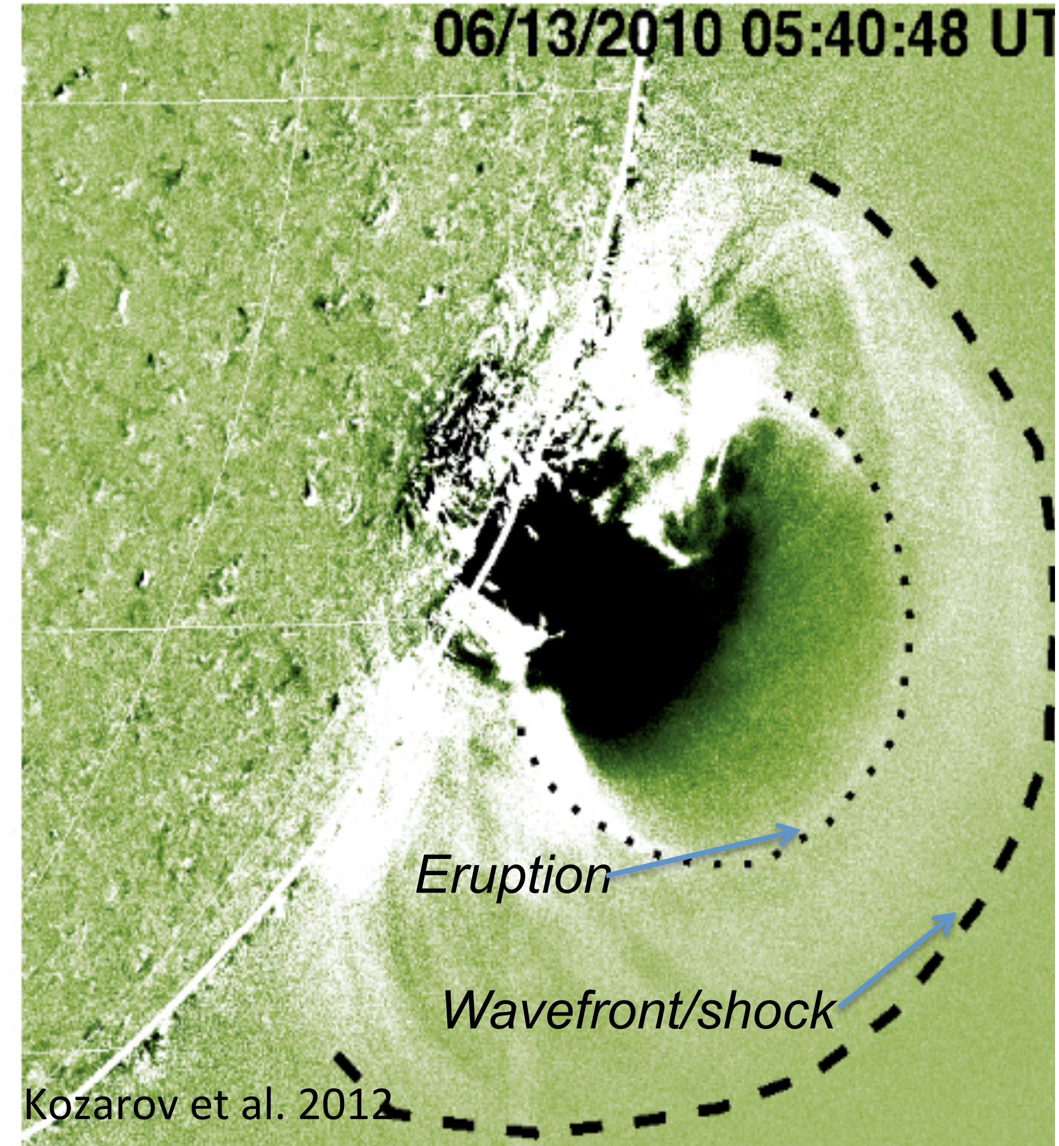
- Approaching 1-yr Free Space Dose Limits at Mars
- See more at http://prediccs.sr.unh.edu/

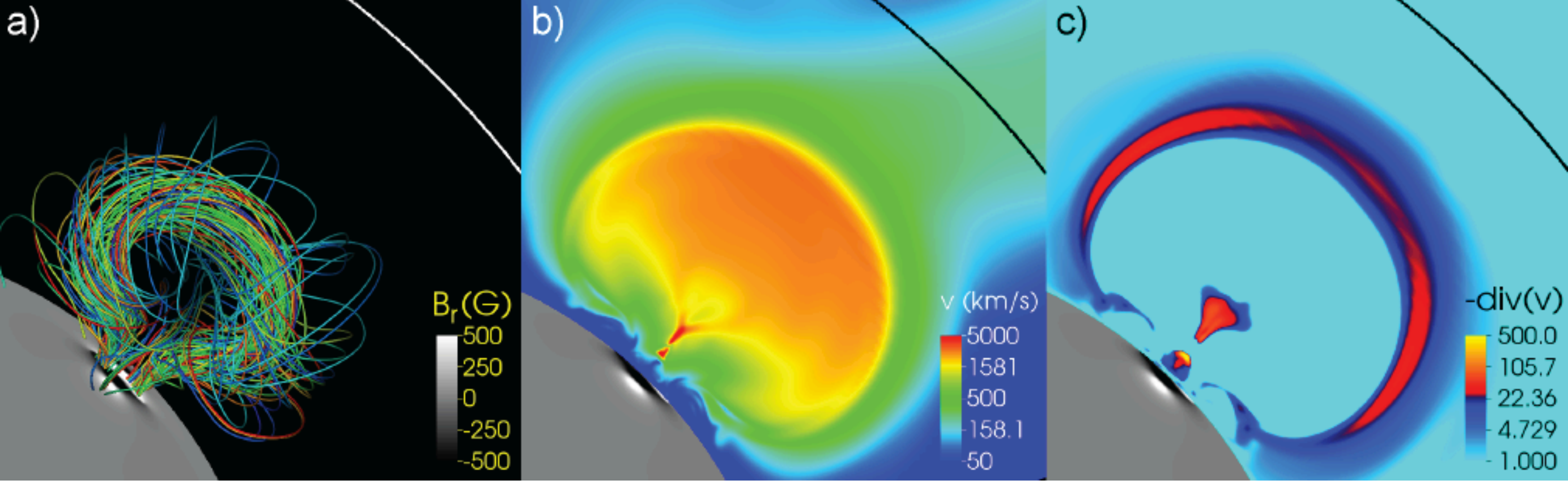


Remote Observations Showing Events from the Low Corona

Formation of acceleration regions (from shocks and compressions) in the low corona critical missing piece in understanding sudden SEP onsets.

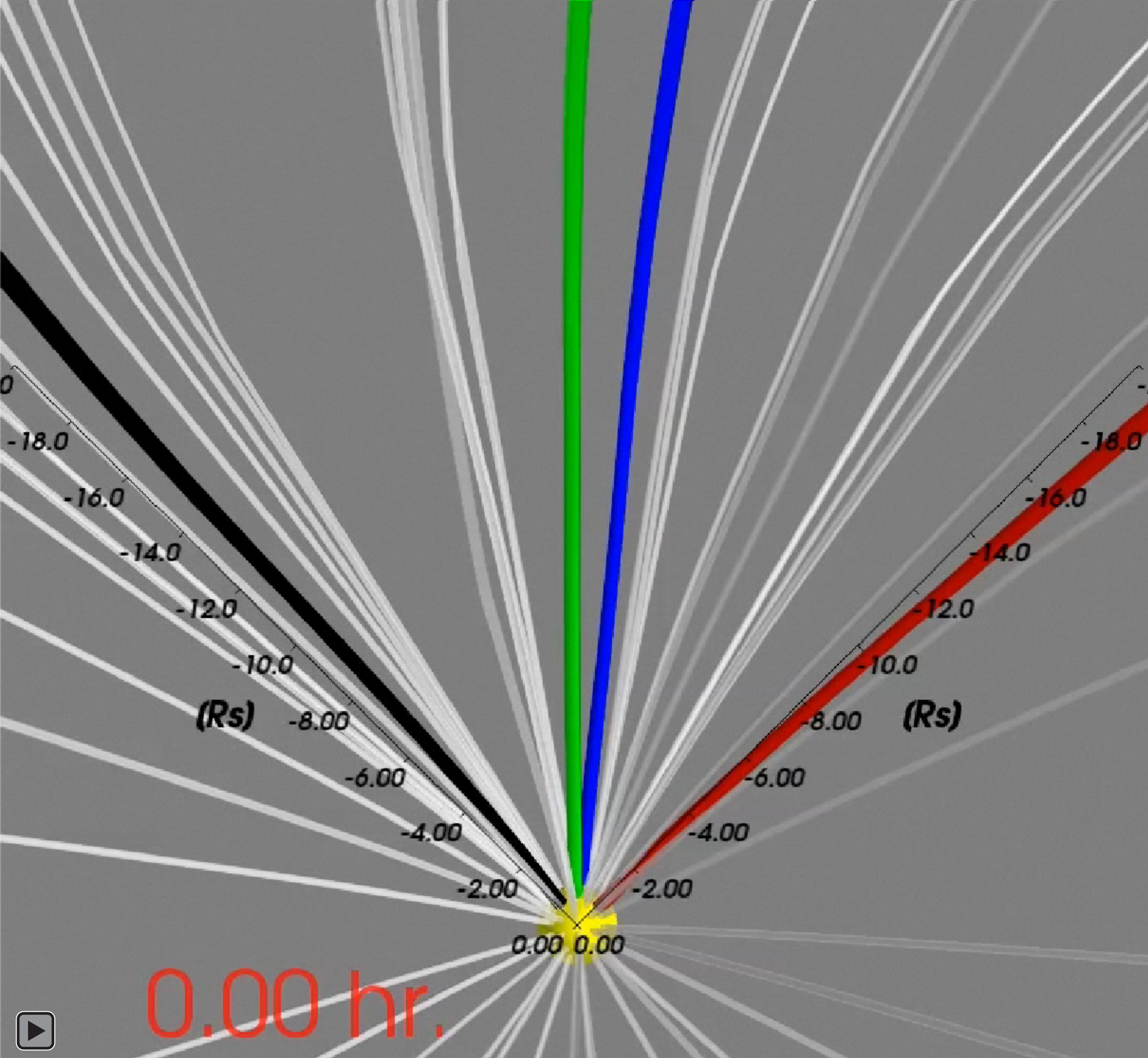
- AIA/211 image shows a stage of the 2010 June 13 coronal wave with
- The shock was formed at ~1.2 Rs and observed here at 1.4 Rs.





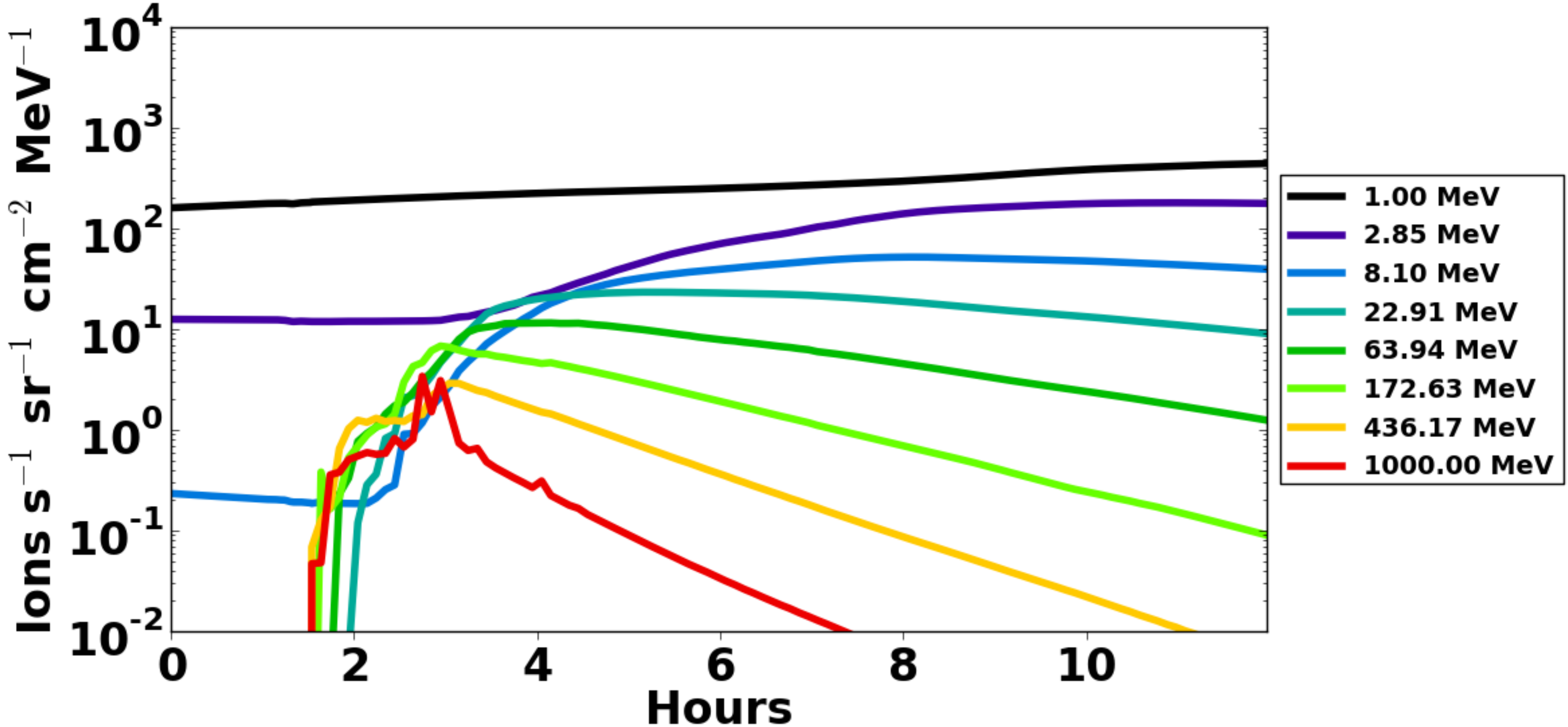
Titov et al., 2013

- Insert modified version of the flux rope model by Titov & Demoulin (1999) above the central polarity inversion line of AR.
  - AR + Flux Rope total unsigned flux of 7.5 x 10^{22} Mx
  - Max radial-field strength of 1070 G at the photospheric level

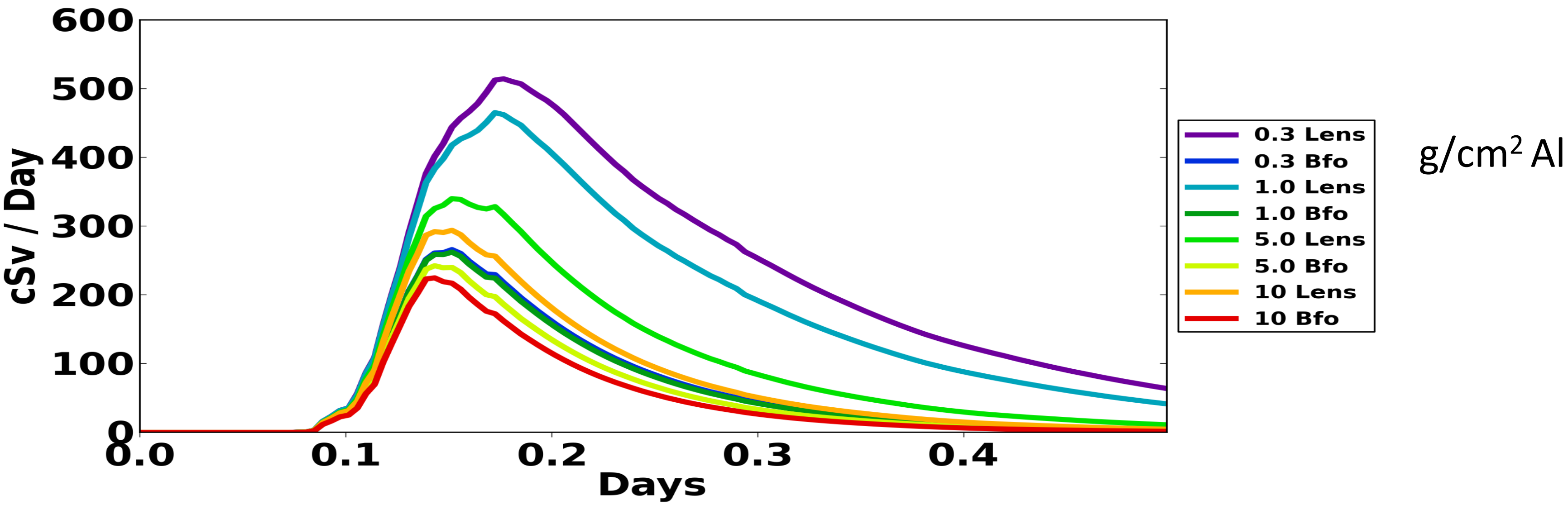


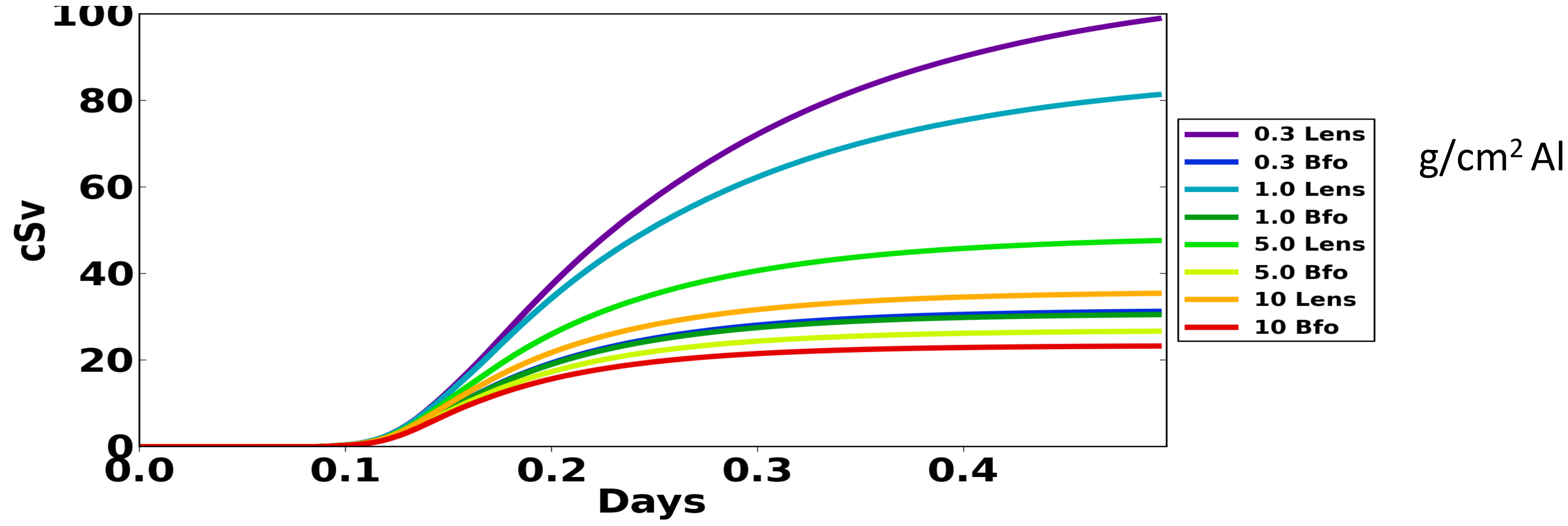
- ***C-SWEPA simulation of CME release from solar corona and coupled into solar wind***
- ***Colored field lines show particularly strong distortions of the magnetic field by the explosive plasma flow***

Using coupled MAS-EPREM simulations, C-SWEPA links coronal conditions, CMEs and associated shocks and transients to solar energetic particles, solar wind conditions, and ultimately to time-dependent radiation exposure. Shown are the results for particle differential energy fluxes at 1 AU from the event.



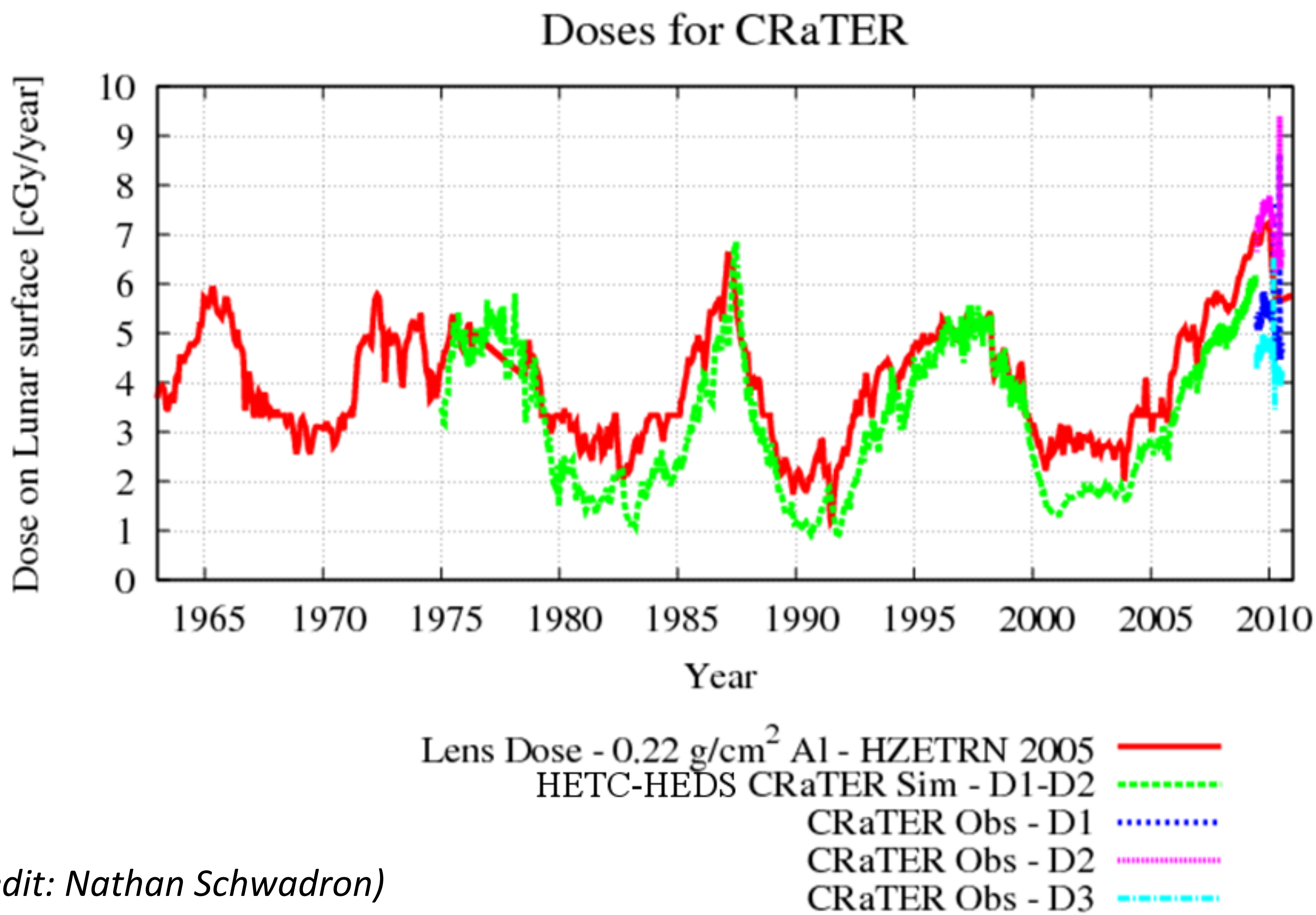
Resulting integrated dose and dose rate equivalents for Lens and Blood Forming Organs (BFO) behind different levels of shielding. The results here show 10's of cSv even for well-shielded (10 g/cm² Al) BFO dose equivalents, indicating a radiation hazard that approaches the 30-Day Limit (25 cSv) in roughly 2 hours





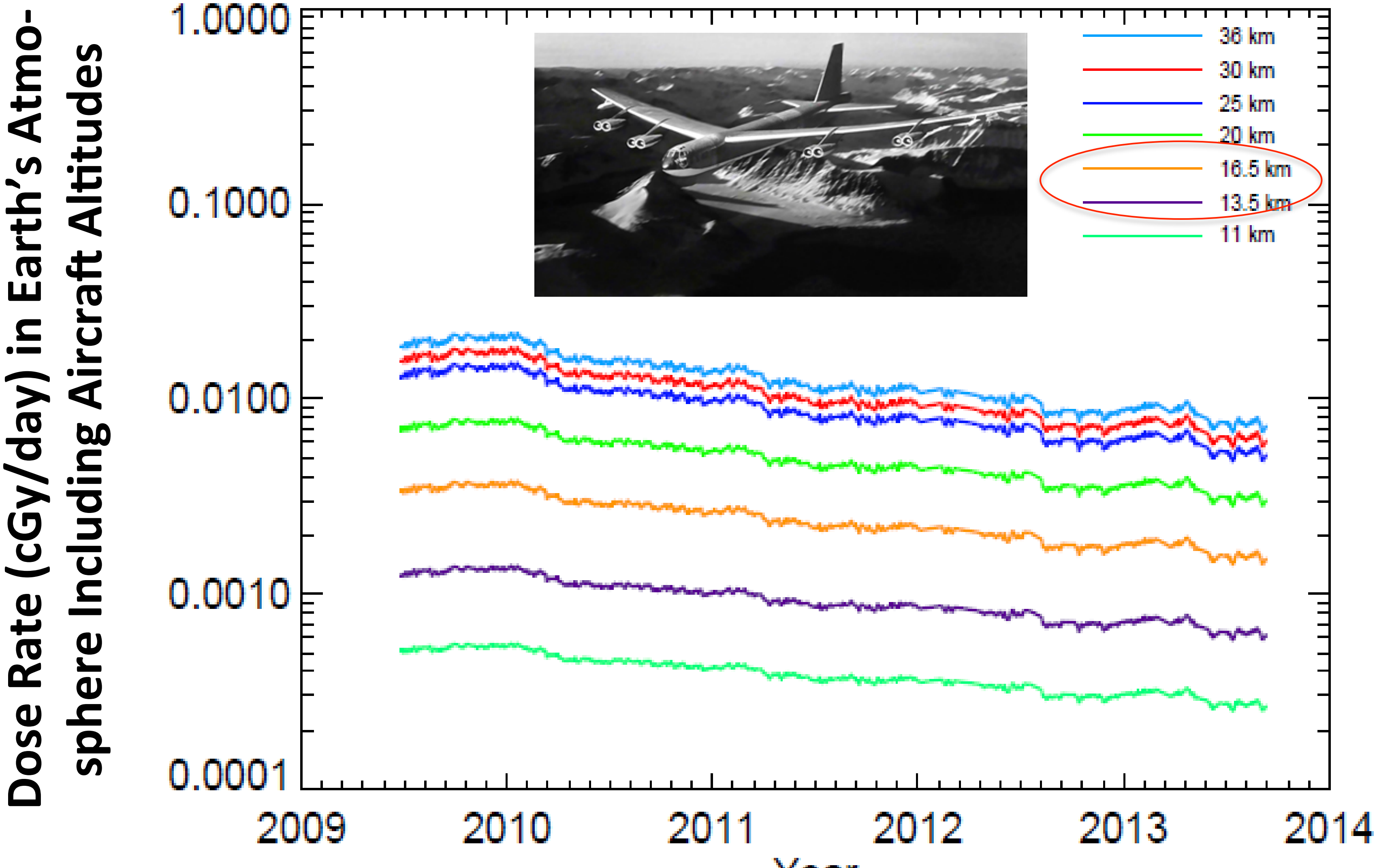
Modeling Space Radiation = SEP + GCR

Validated models new tool for science prediction (forecasting) and for engineering design (shielding)



(Credit: Nathan Schwadron)

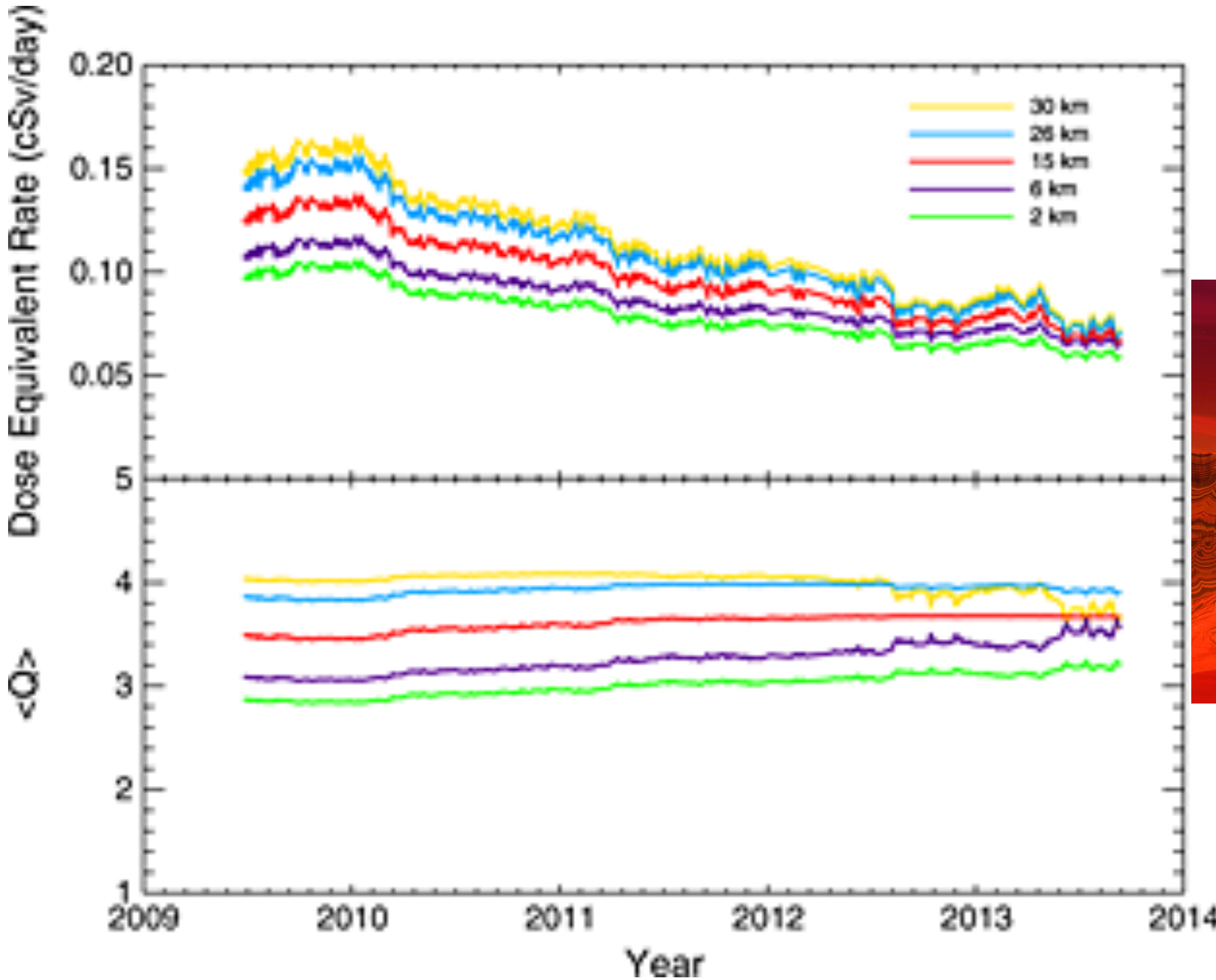
GCR dose rates in Earth's atmosphere. Dose rates computed behind 1.0 g/cm2 shielding. Dose rate at 36 km is ~34x larger than at 11 km in 2009 during extended solar min. Ratio decreases during progression to solar max, falling to ~26 by 2013.

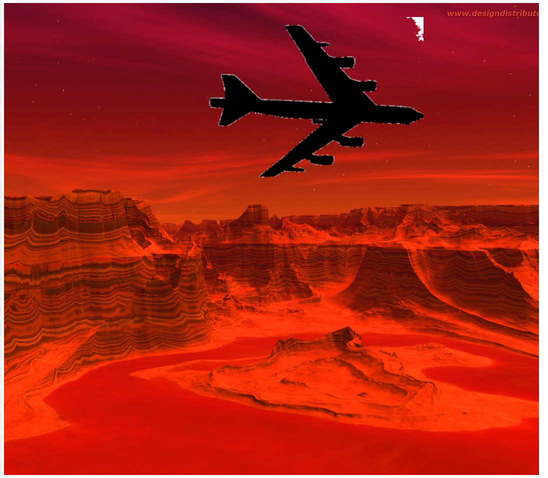


From Joyce et al., Space Weather, 2013 *(See also work by Mertens et al., Tobiska et al. and Phillips et al.)*

Impacts THROUGOUT the Heliosphere: Here, There, & Everywhere!

GCR dose rates in Martian atmosphere (at B52 altitudes?) versus altitude as well as quality factor <Q>. Unlike at Earth, dose equivalent differs significantly from dose rate values, being ~4x greater at highest altitude and 3 at lowest.





Summary

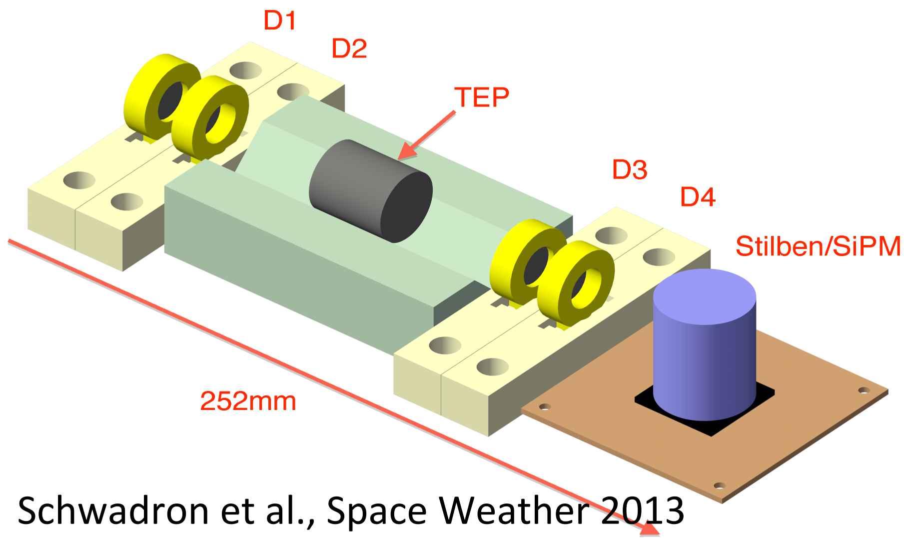
- Radiation effects for humans in space present a serious health and safety risk
- Ionizing radiation sources are multifold: galactic cosmic rays (GCR), solar protons, and radiation belts – almost no where is safe!!
- Deep solar minimum produced space-age high GCR – radiation dose manageable for lunar missions, challenge for Mars mission
- Sun's activity is now at solar maximum and unremarkable
  - Sun has thrown us more powerful events in last few years
  - Some have posed significant radiation concerns, but manageable
  - However, history shows that Sun is capable of BIGGER events of grave concern even during grand lulls – stay tuned!
- Measurements being used to improve predictive models which can be used to:
  - Improve radiation shielding technologies
  - Improve NASA's ability to forecast space radiation "climate" and space


THE
END
MADE AT
SHEPPERTON
STUDIOS,
ENGLAND BY
HAWK
FILMS LTD.

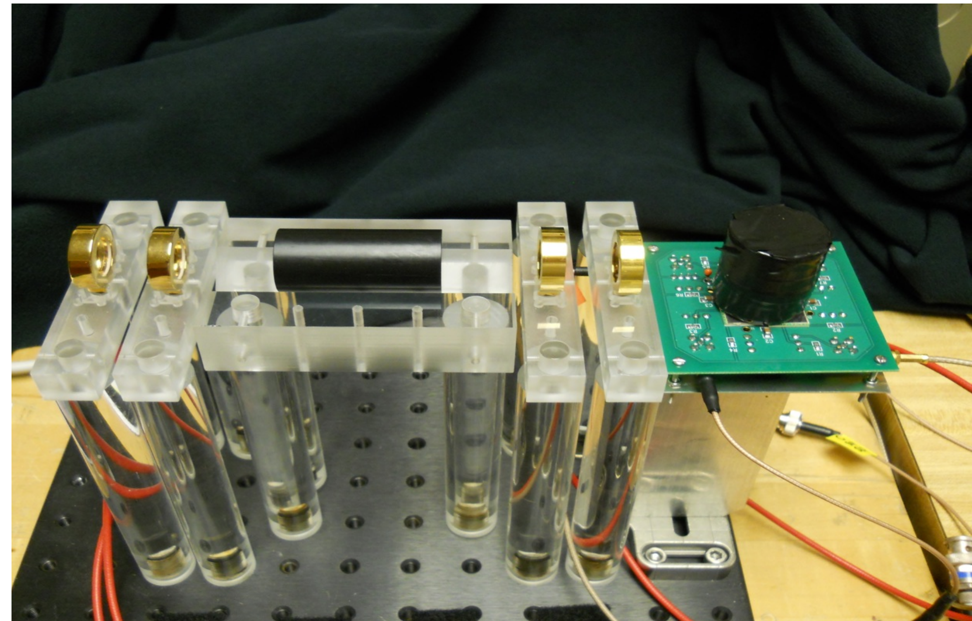
Summary

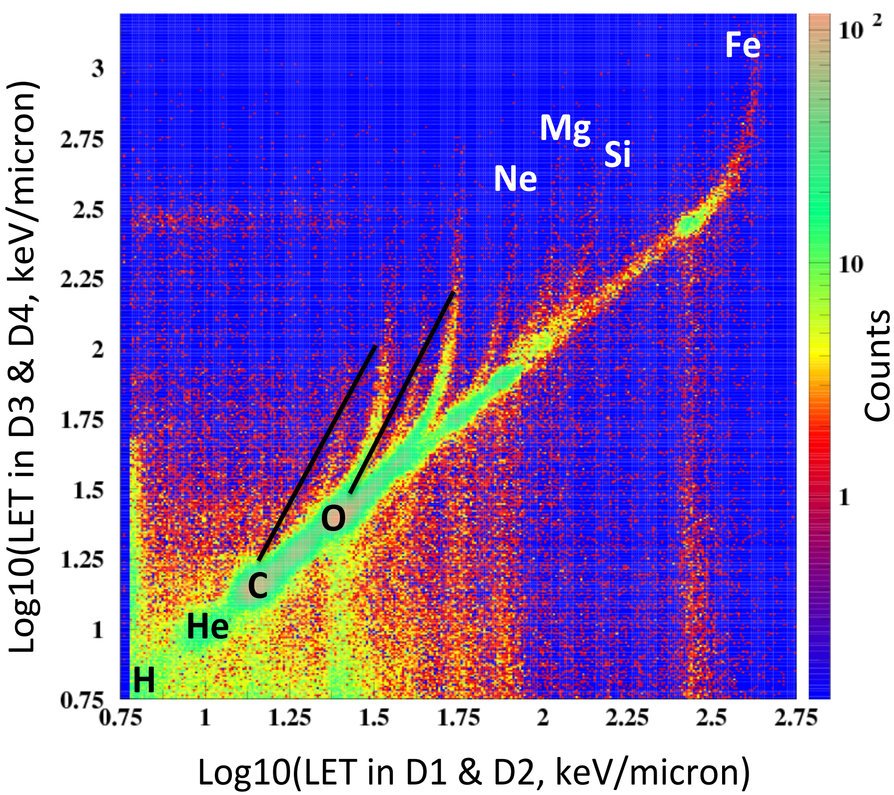
- Worsening radiation environment from anomalously low solar activity
  - Cycle 23-24 Protracted Minimum
  - Cycle 24 Mini Maximum
- Solar Maximum may be the time to perform long-duration exploration missions
- Threat of large prompt solar events (e.g., July 2012 STEREO event, Russell et al., 2012)

- **Increasingly Difficult Problem!**

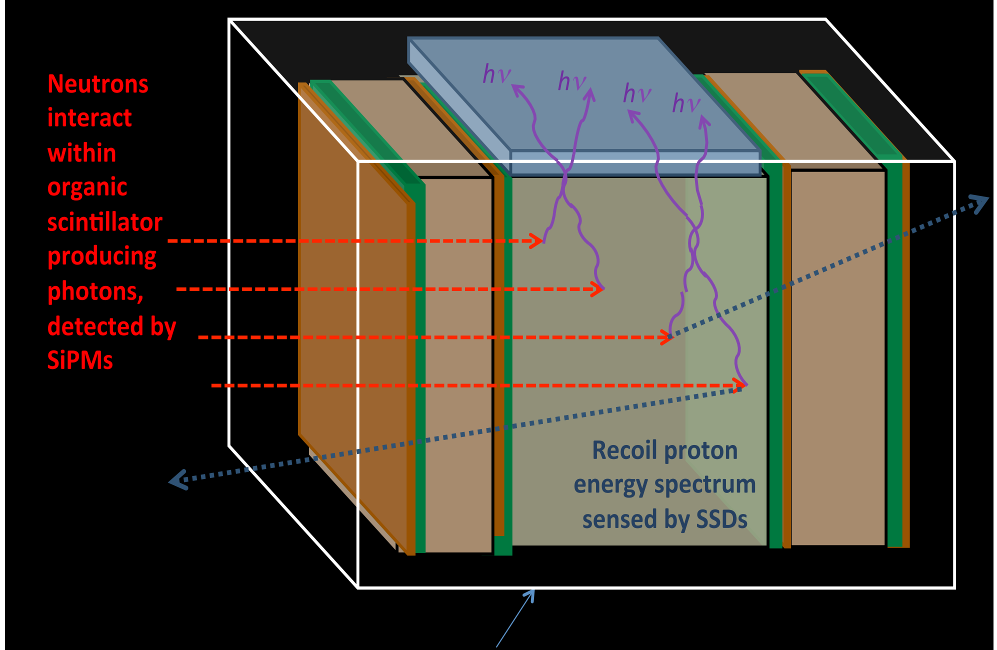


Schwadron et al., Space Weather 2013

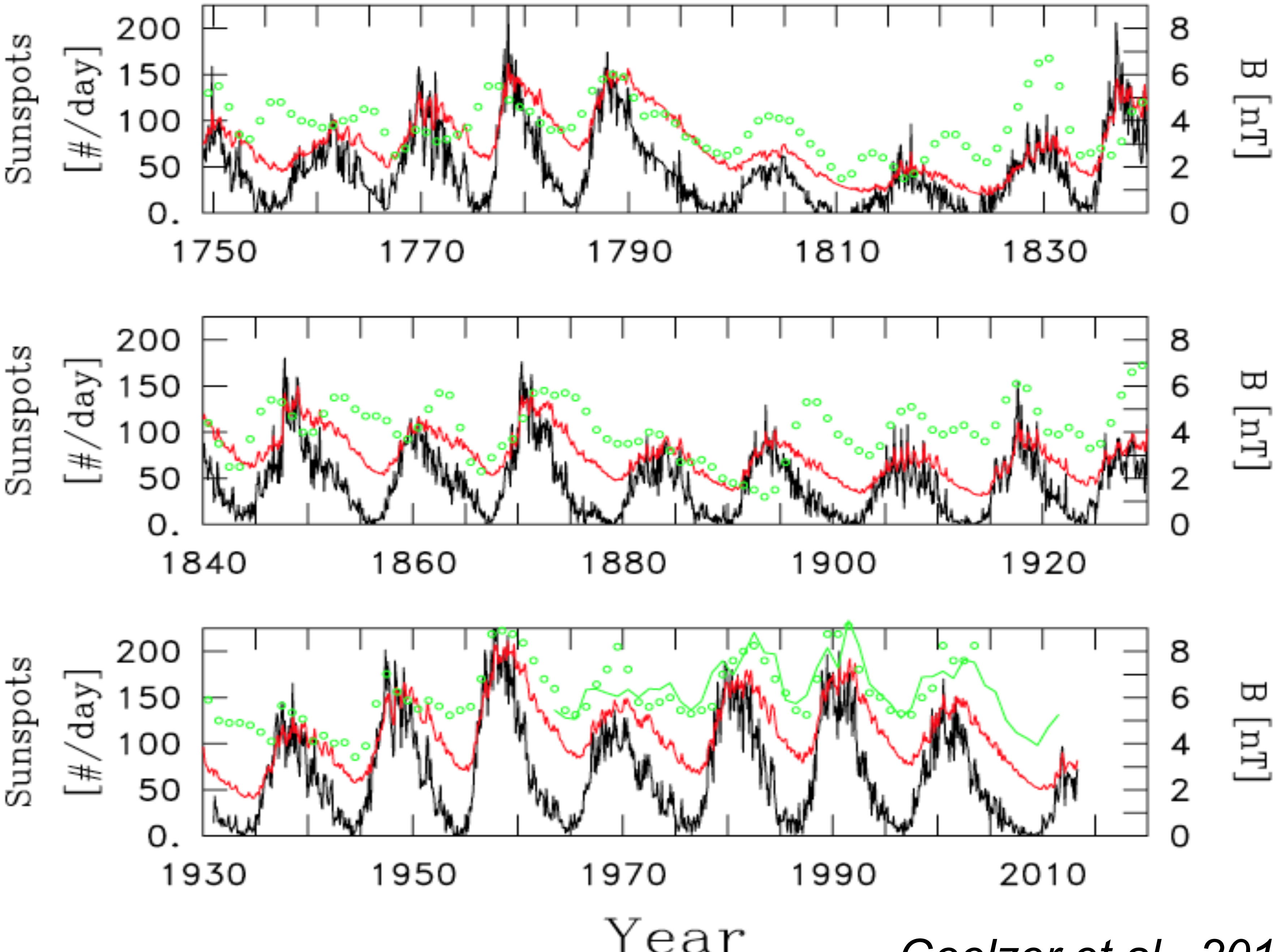




DoSEN Neutron Measurement Concept

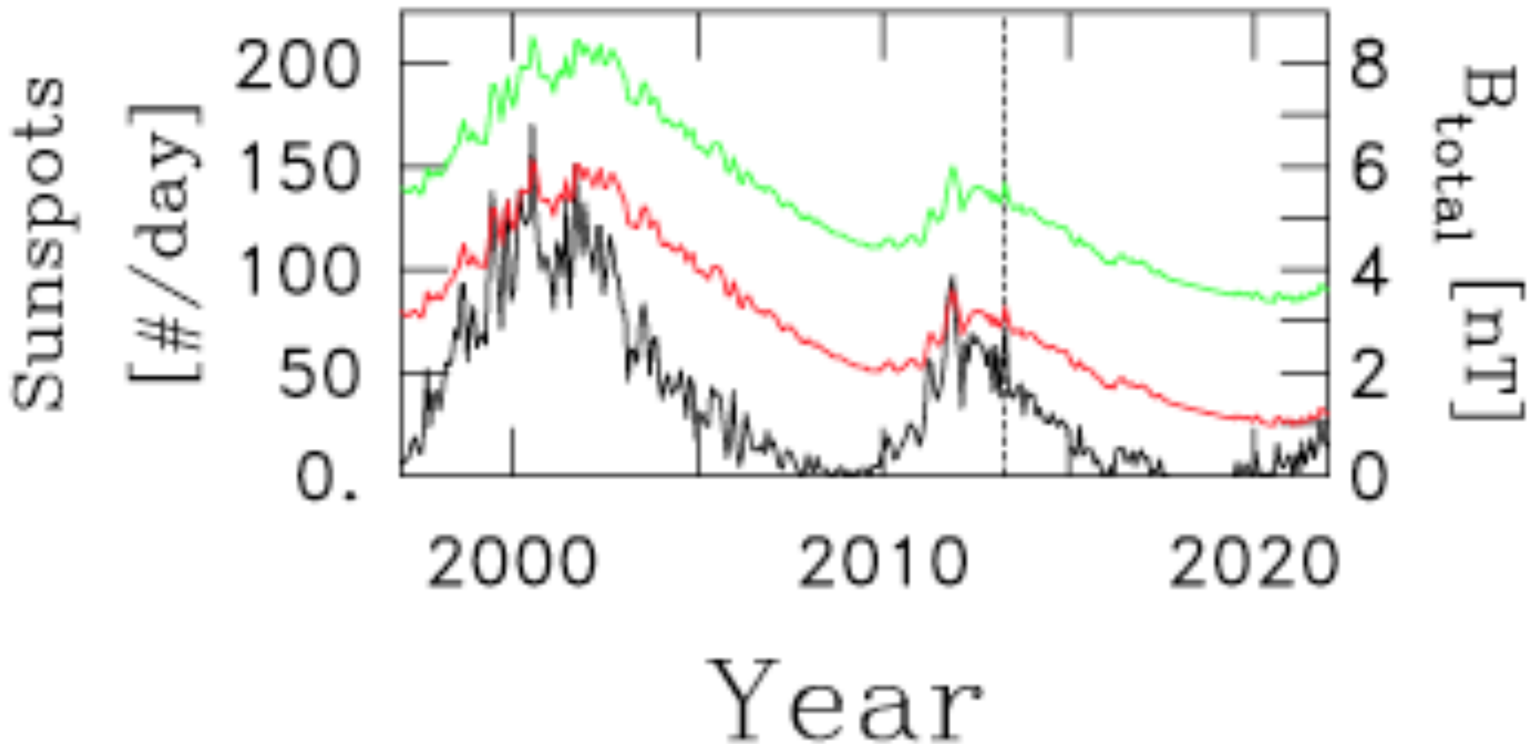


Aluminum DoSEN Enclosure = "Bioeffective" Shield (blocks <10 MeV p+)



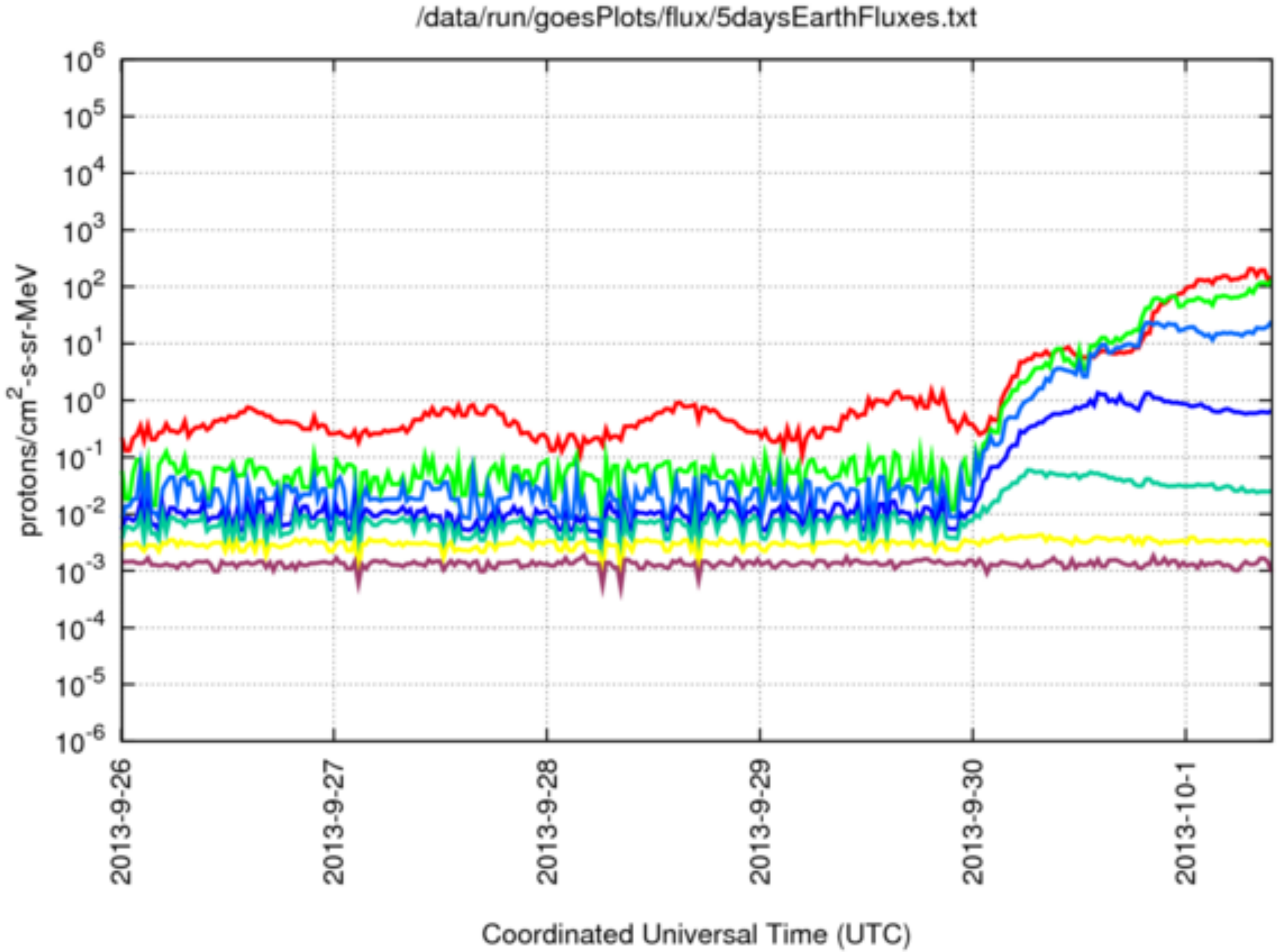
Goelzer et al., 2013

The remarkable evolving Sun



Will the next cycle also look like the Dalton minimum (1807-1840)?

Goelzer et al., 2013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protons/cm2-s-sr-MeV
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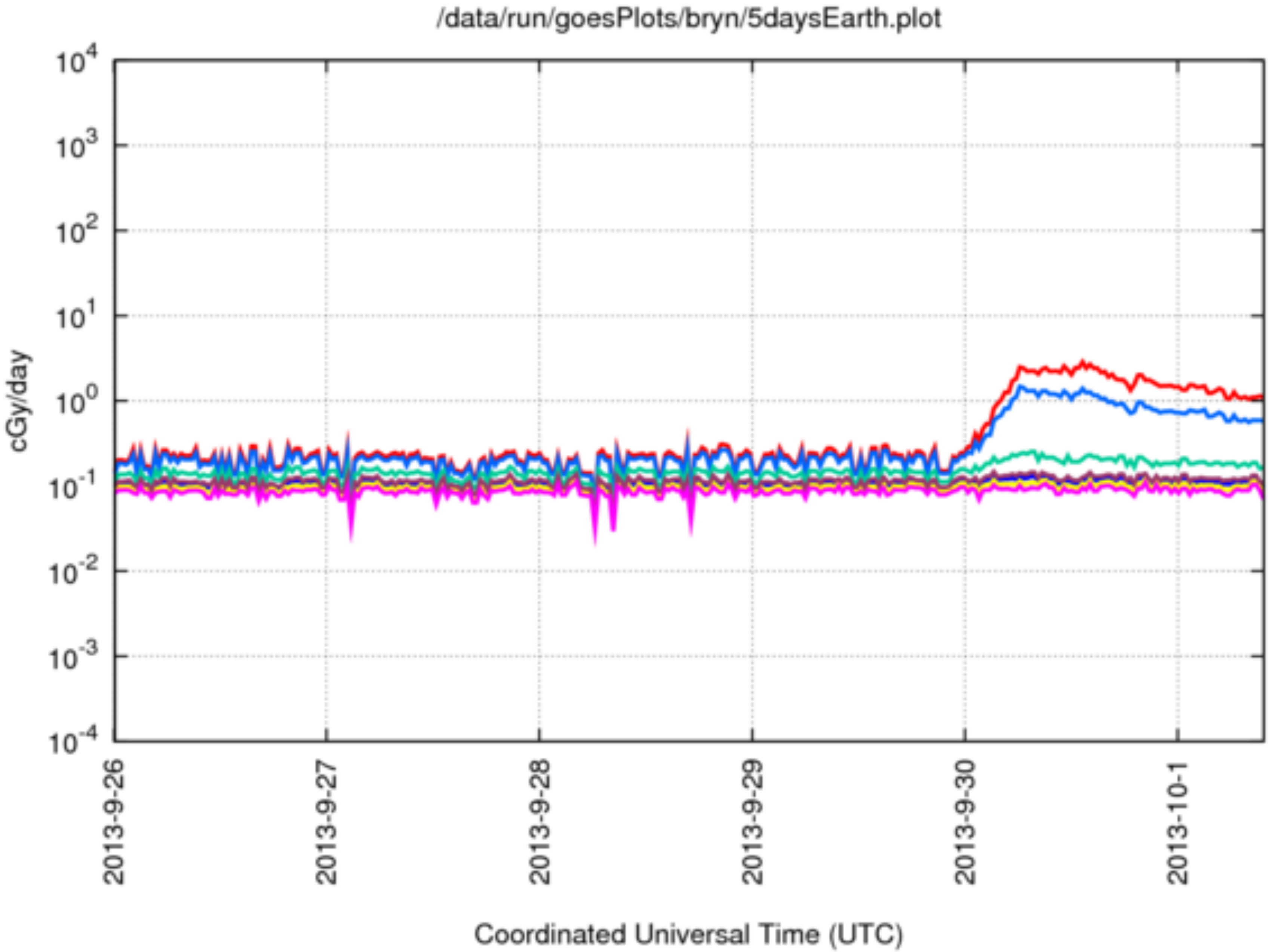
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2013-9-29
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U. Tennessee – EMMREM Accomplishments
NNX07AC14G – L. Townsend

- Lead development of Scenario and Transport code modules
- Provided capability, in near-real-time, to calculate radiation doses and LET spectra for tissue and electronics behind spacecraft aluminum shields using "looping" BRYNTRN code
- Provided database of human organ radiation exposures for Al shielding thicknesses relevant to vehicle and habitat designs anywhere in free space or in Mars atmosphere for GCR and SEP spectra covering the entire solar cycle
- Calculations of doses, dose equivalents and effective dose for GCR and SEP protons at aircraft altitudes in Earth's atmosphere are completed. Heavy ion component calculations are in progress
- Publications (author/coauthor)

  - 10 journal articles

  - 4 invited paper presentations

  - 15 contributed paper presentations
- 3 graduate students supported

Transition to Prediction & Operations

- New ESMD/LRO Predictive Model

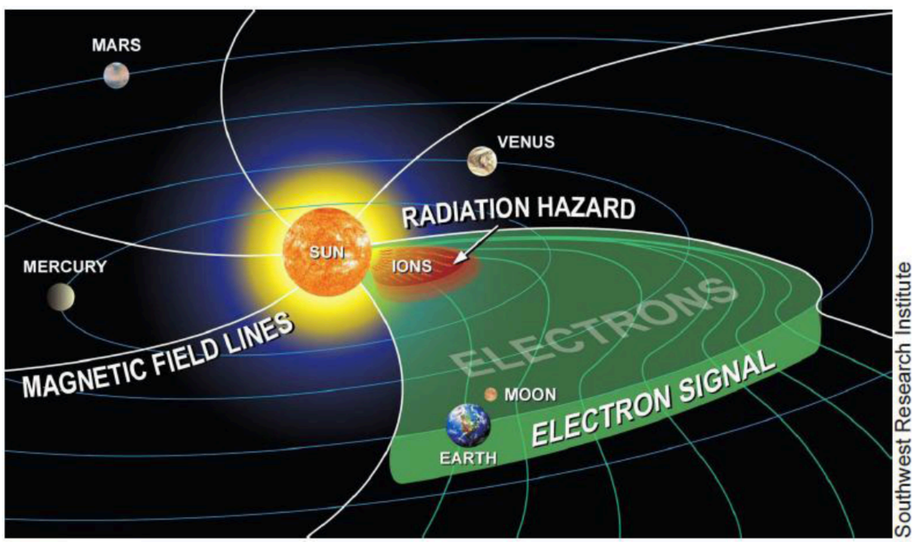


Figure from Posner et al. (2009) demonstrating how relativistic electrons racing ahead of SEP ions provide an early warning of the radiation hazard to follow up to one hour later.

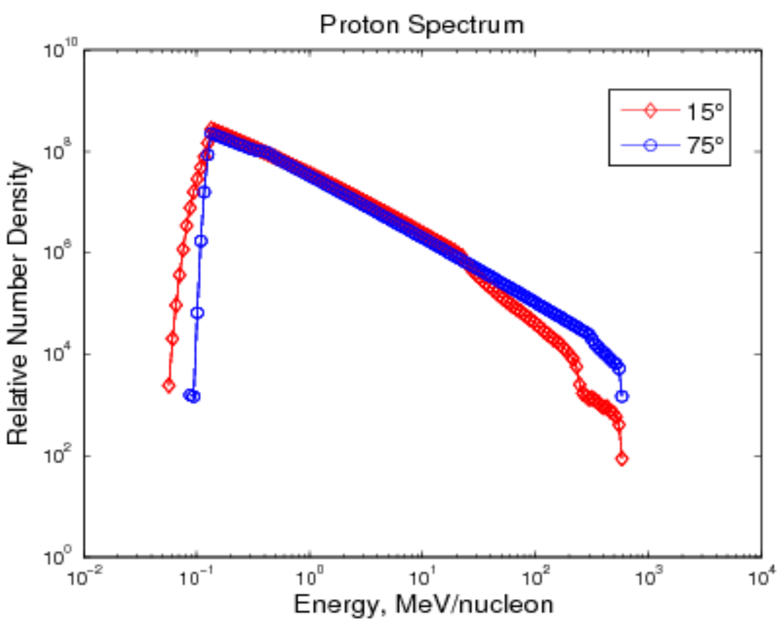
Task Description	Value to ESMD
(1) SEP Prediction Development	Uses CRaTER observations and existing models to **improve advanced warning of solar proton events**
(2) Radiation Environment Forecasting	Develops analysis and modeling tool combined with CRaTER observations to **extend prediction of the radiation environment well beyond low Earth orbit**, not only at Moon but also throughout the inner heliosphere, including at Earth, Moon, Mars, Asteroids, and Comets

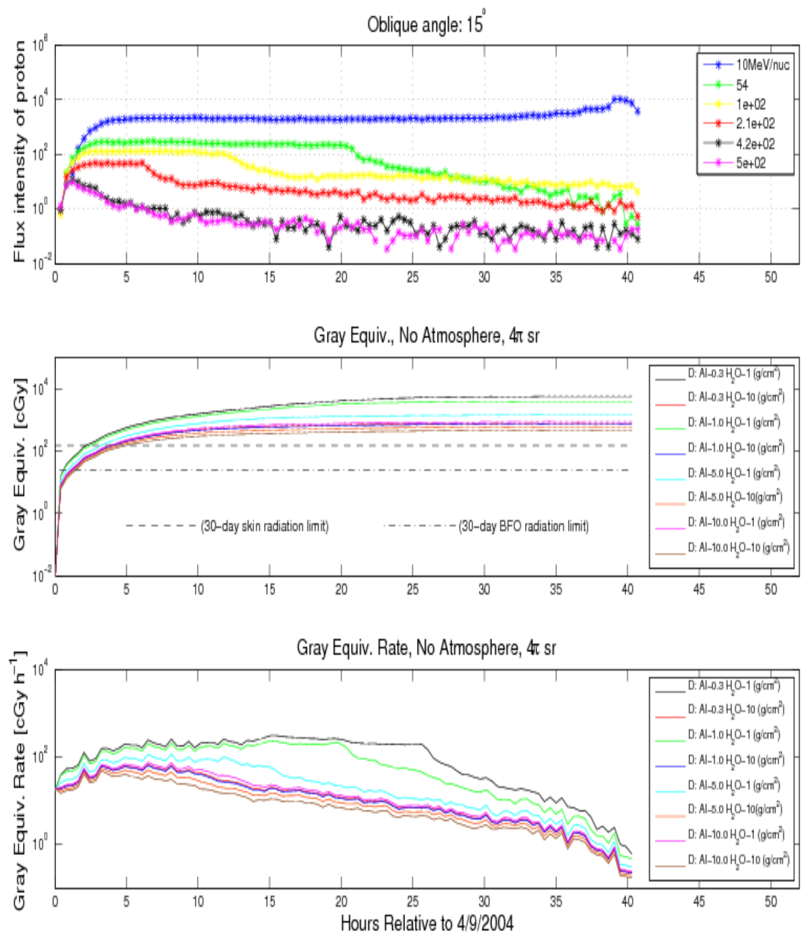
Next Steps for EMMREM

- Transition to Operations and Predictive Models
- Development of Comprehensive Risk Models
- Coupling between MHD & EPREM
- Continued development of PATH into a predictive model

Modeling Large SEP Events with PATH Code

- Zank et al., AGU, 2010





Worsening Radiation Environment

N. A. Schwadron[1], J. B. Blake[2], A. W. Case[3], C. Joyce[1], J. Kasper[3,4], J. Keller[5], J. Mazur[2], N. Petro[5], M. Quinn[1], C. Smith[1], S. Smith[1], H. E. Spence[1], L. Townsend[3], J. K. Wilson[1], C. Zeitlin[7]

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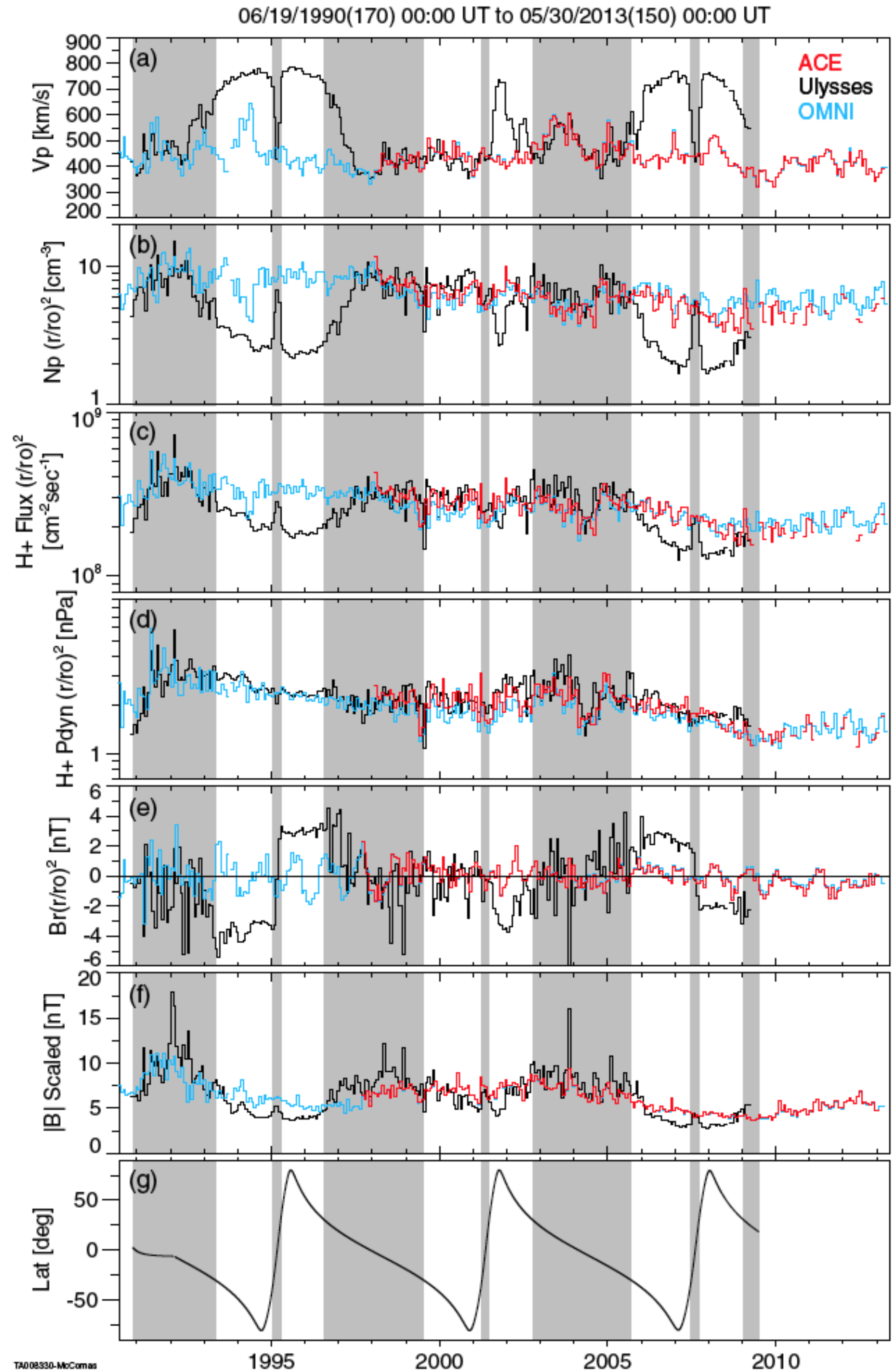
Protracted Min (23) and Mini Max (24)

- Dropping solar wind
  - Flux
  - Pressure
  - Magnetic Field
- Continues trend observed by Ulysses

McComas et al., ApJ, 2013

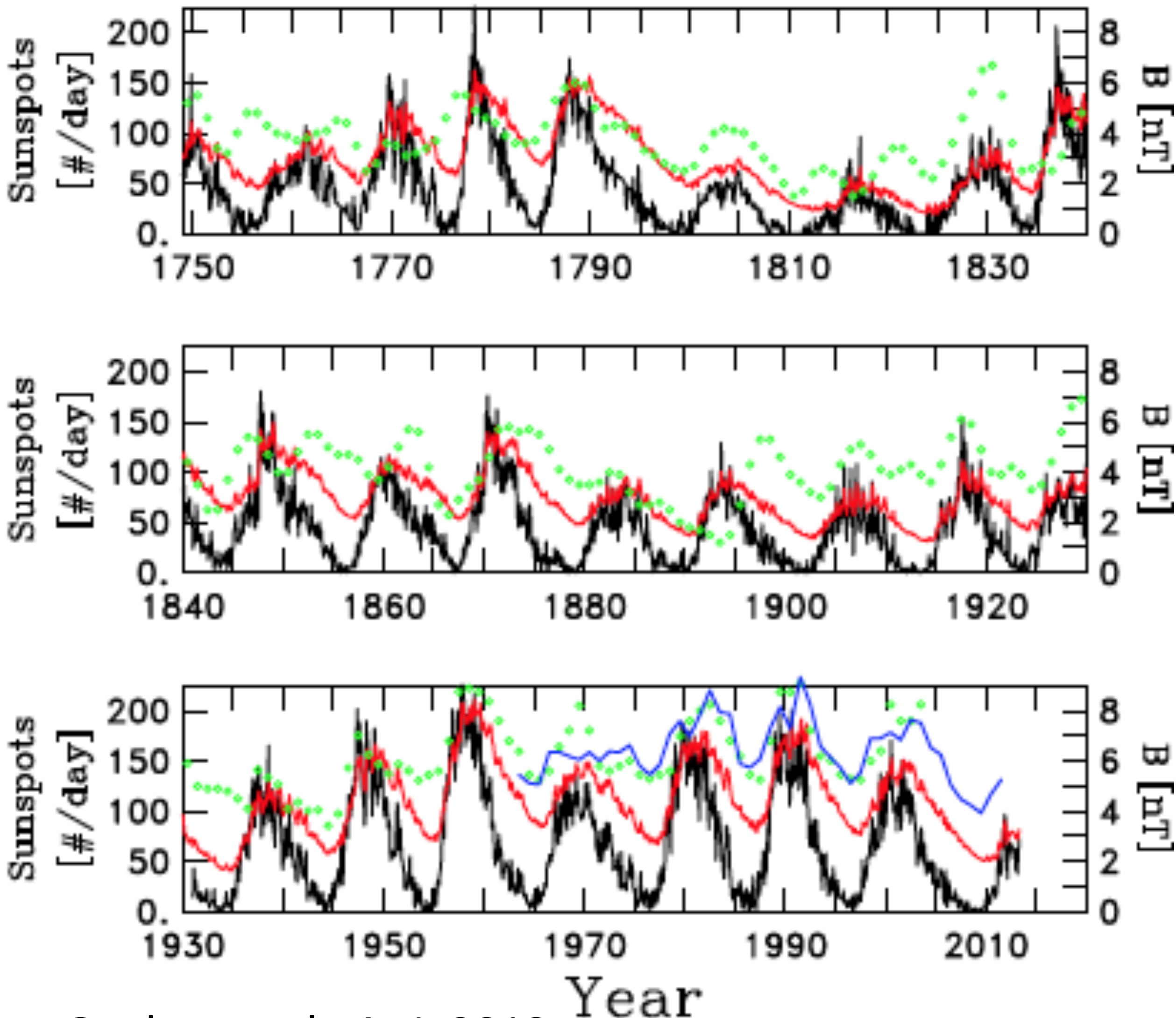


Reductions in Magnetic Field & SSN

- SSN (black)
- Predicted (red)
- OMNI (blue)
- ^{10}Be (green)
- Magnetic Flux Balance (Schwadron et al.,, 2010)

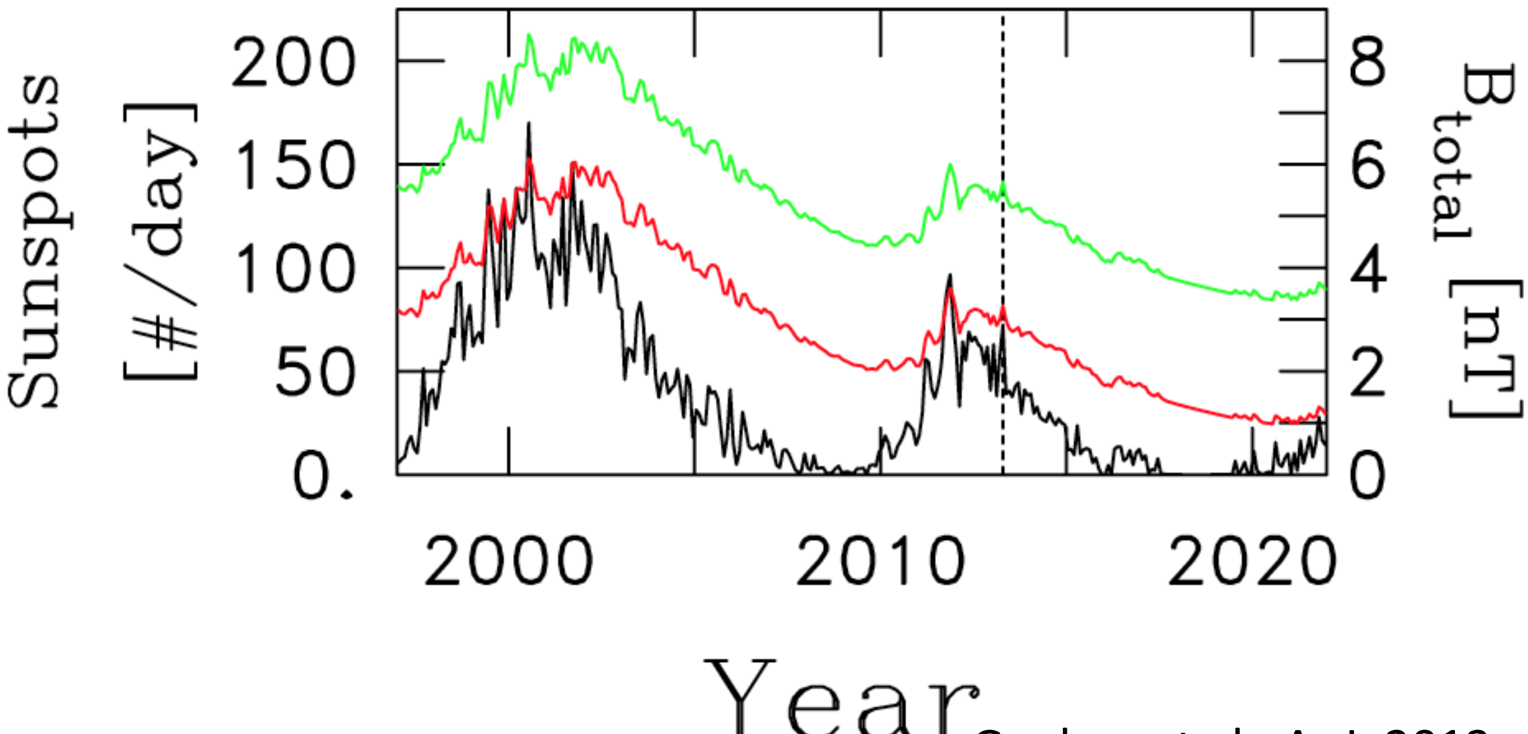
$$\frac{d\Phi_{ej}}{dt} = f\,(1-D)\,\phi_{CME} - \\ - \Phi_{ej}\left(\frac{1}{\tau_{ic}} + \frac{1}{\tau_d} + \frac{1}{\tau_o}\right)$$

$$\frac{d\Phi_o}{dt} = -\frac{\Phi_o - \Phi_{flr}}{\tau_d} + \frac{\Phi_{ej}}{\tau_o}.$$



Goelzer et al., ApJ, 2013

Continued Decay of Magnetic Flux in the Dalton-like Minimum



Goelzer et al., ApJ, 2013

Slab Turbulence Model

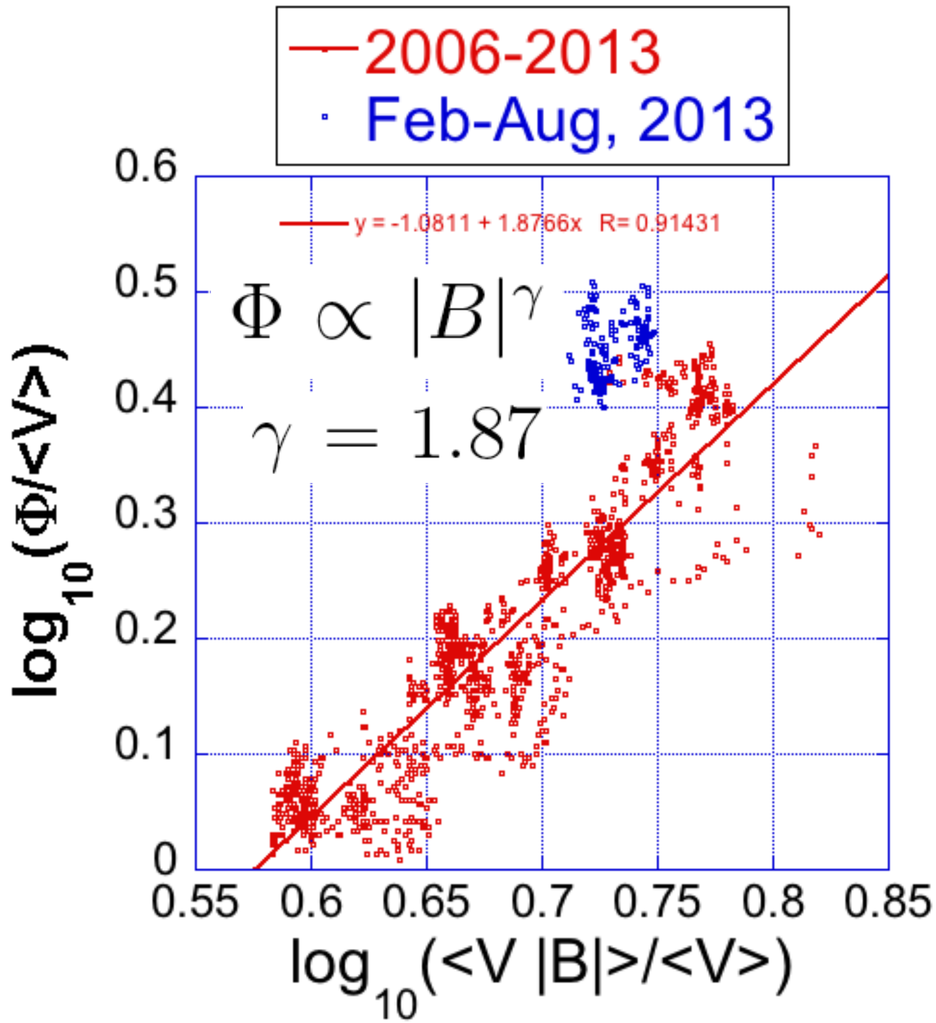
- Modulation Potential

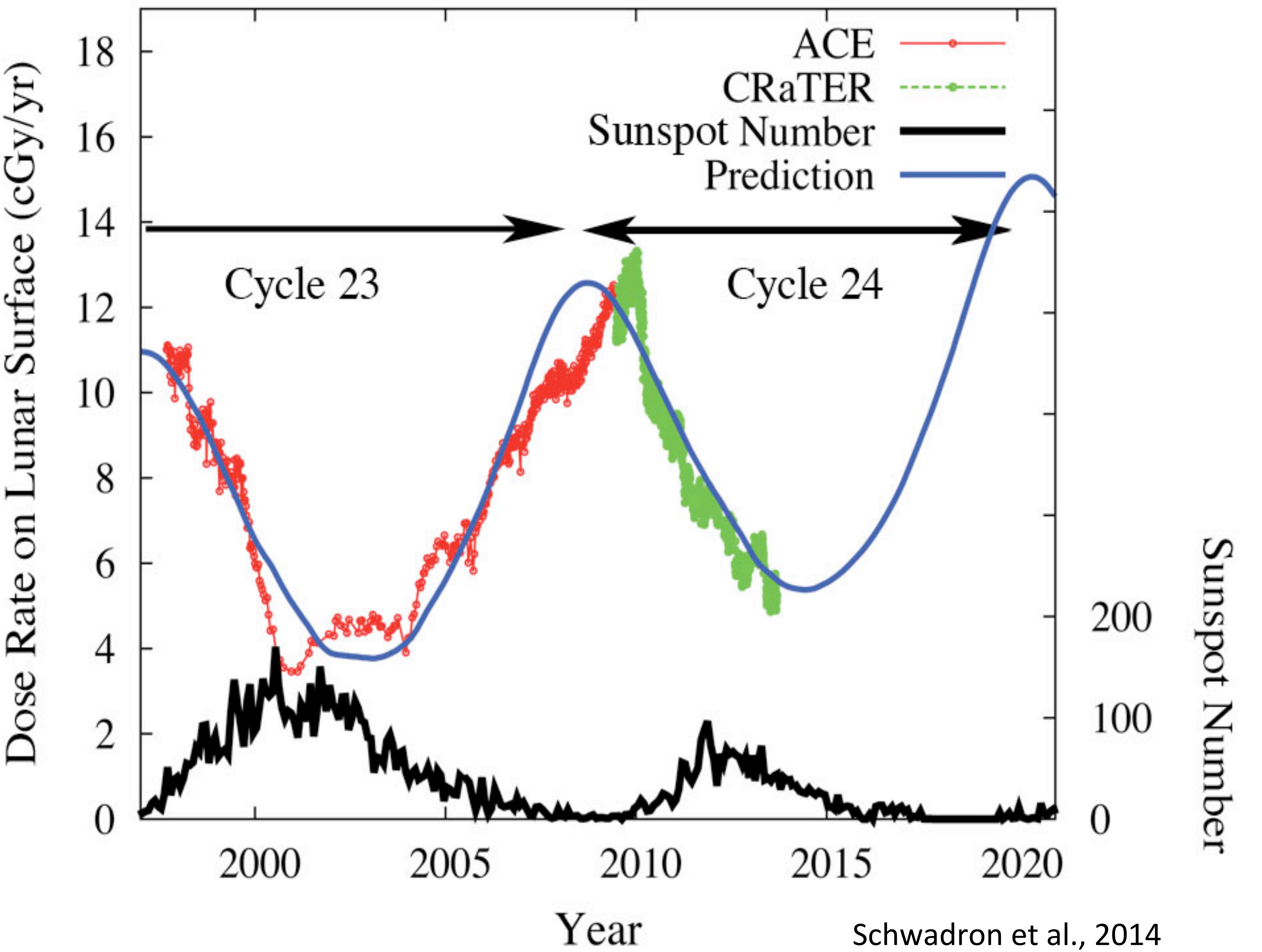
$$\Phi = |Ze|\phi(r)$$

$$\phi(r) = \int_r^{R_b} dx \frac{V(x)}{3\kappa_1(x)}$$

$$\kappa_{||} \propto r_g^2/F^2 \quad F = \delta B/B$$

$$\Phi \propto B^2$$





Schwadron et al., 2014

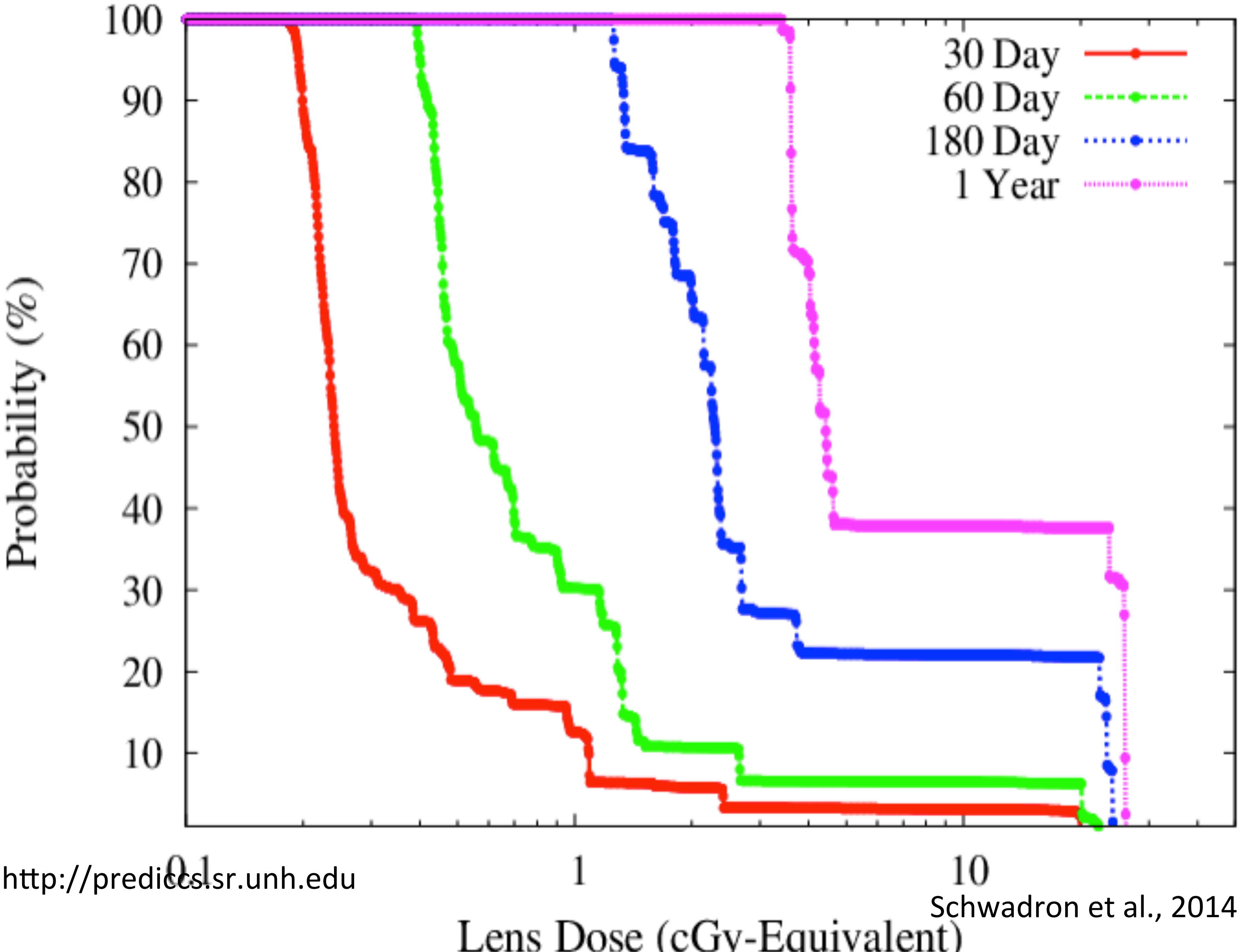
3% Risk for Exposure Induced Death

Age	3% REID Maies E (cSv)	3% REID Femails E (cSv)
30	62	47
45	95	75
55	147	112

Managing Space Radiation Risk in the New Era of Space Exploration
Committee on the Evaluation of Radiation Shielding for Space Exploration, National Research Council 2008

Time (Cycle)	Dose Eq. Rate <Q>=5.8 (cSv/dy)	Days to 3% REID (30 yr old male)	Days to 3% REID (30 yr old female)	Dose Eq. Rate <Q>=3.8 (cSv/dy)	Days to 3% REID (30 yr old male)	Days to 3% REID (30 yr old female)
1997.0 (Min 22-23)	0.35	180	130	0.23	270	200
2003.0 (Max 23)	0.13	490	370	0.08	740	560
2008.7 (Min 23-24)	0.40	155	120	0.26	240	179
2014.0 (Max 24)	0.18	350	270	0.12	530	400
2020 (Min 24-25)	0.47	130	100	0.31	200	150

Schwadron et al., 2014



http://prediccs.sr.unh.edu

Schwadron et al., 2014